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Evaluation of Ground Pressure, Bearing Capacity, and Sinkage in Rigid-Flexible Tracked Vehicles on Characterized Terrain in Laboratory Conditions

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Abstract: In the field of engineering, tracked vehicles play a significant role in accessing challenging terrains. Maintaining trafficability is of the utmost importance when it comes to tracked vehicles traversing rugged terrains; it provides stability, traction, and adaptability for a wide range of applications, including deep-sea exploration. The terrain characteristics pertain to the interactions that determine the mobility of tracked vehicles. Traditional Terramechanics models are inadequate in depicting the correlation between tracks and soil. An important issue is the lack of consideration for the moisture content in the soil and the rate at which sinking occurs in these models. Examining sinkage speed helps describe the ability of tracked vehicles to move at high speeds. The focus is on the critical factors influencing the mobility of tracked vehicles, precisely the sinkage speed and its relationship with pressure. Experimental tests in a soil bin, utilizing Bentonite/Diatom sediment soil, aim to measure these terrain factors. The study introduces a rubber-tracked vehicle, pressure, and moisture sensors to monitor pressure sinkage and moisture, evaluating cohesive soils (Bentonite/Diatom) in combination with sand and gravel mixtures. Findings reveal that higher moisture content in Bentonite soil leads to increased track slippage and sinkage compared to Diatom soil. Regarding soil behavior, diatom soil exhibited notable compaction and sinkage characteristics in contrast to bentonite soil. The distinct behaviors of these soils underscore the complexity of terrains, emphasizing the need for a meticulous understanding of soil properties before applying them in natural environments. Furthermore, this study contributes precision in assessing natural terrains, enhancing tracked vehicle design, and advancing terrain mechanics comprehension for off-road exploration. This knowledge contributes to better vehicle design and a deeper comprehension of terrain mechanics.

Keywords: terramechanics; sensors; tracked vehicle; ground pressure; soil bin; bearing capacity; pressure-sinkage

1. Introduction

Terramechanics is instrumental in shaping the performance of off-road vehicles as this discipline emphasizes the dynamic interaction between vehicles and terrain [1]. This domain is of paramount importance for the development and accessibility of off-road equipment designed for particular terrain categories. Over the years, researchers have devised various methodologies to probe the mobility of these vehicles [2–7], given their critical role in navigating challenging terrains [8,9]. Tracked vehicles offer numerous advantages in off-road situations, unlike their wheeled counterparts. Their design ensures a broader contact surface with the ground, leading to uniform weight distribution and a reduced risk of sinking. This design feature has garnered prominence across sectors such as the military, construction, agriculture, and mining [10–12].

Tracked vehicles equipped with rubber tracks promise enhanced grip, lower ground pressure, and elevated mobility. Understanding their interaction across different soil beds is essential. Further, the tracked vehicles facilitate accurate monitoring and analysis of different soils' behavior under varying moisture conditions [13,14]. Their capacity to traverse various types of surfaces results from

 doi:10.20944/preprints202401.2189.v1

the intricate correlation between the vehicle's characteristics and the natural qualities of soil, including texture, moisture level, temperature, and structural stability of the terrain.

When used off-road, a tracked vehicle encounters opposition to movements that consist of internal and external factors. The presence of internal resistance pertaining to intrinsic factors such as friction and vibrations influences the vehicle's motion over different terrains. On the other hand, external resistance results from soil deformation rather than soil thrust generation. The chief factors related to external resistance are the creation of ruts and sinkage, notably the compacting of soil beneath the tracks [15]. Thus far, the prevailing consensus has been that bulldozing and compaction resistance are the two primary elements of external resistance [1,6,7]. Bulldozing resistance is the opposition faced when soil is pushed forward by bulldozing at the front part of the railroads. Resistance occurs when the amount of sinking is more significant than the vertical space available for the vehicle. However, there is a concern that this resistance is not evident when the sinkage is lower than the clearing threshold [1,16,17].

It is essential to recognize the relationship between soil compaction and vehicle encounters when considering the design and performance of off-road vehicles. A recent study [5] has outlined a multitude of techniques for applying data from plate-loading experiments in civil engineering and off-road mobility. One notable contribution is an approximate pressure-sinkage model that considers plate size and two soil parameters. As vehicles apply force to the soil, it undergoes compression, leading to increased track sinkage, primarily due to soil compaction and particle transfer beneath the track. The dynamic interaction between soil and vehicle tracks involves tractive effort and motion resistance, influencing vehicle mobility.

Researchers like Bekker [15], Wong [18], Harnisch and Lach [17], and Wong [1] have expanded the pressure-sinkage model, while Benoit and Gotteland [19] introduced a model unaffected by pressure plate shape. Mohtashami and Liu et al. [20,21]examined soil and vehicle factors in rut formation. Alaoui and Diserens [22] studied the impact of soil structure on heavy vehicles. To address the dynamic nature of track-terrain interactions, Meirion-Griffith and Spenko [23], Solis [24], Szpaczyńska [25], and Hu [26] have developed enhanced models.

Soil bins have been instrumental in this study, allowing controlled experiments to explore the intricate dynamics between machinery and soil in laboratory conditions[9]. The previous studies collectively highlight the versatile applications of soil bins in investigating soil-vehicle pressure sinkage, soil-machine interactions, energy dissipation, and the performance attributes of agricultural machinery, emphasizing the significant role of soil bins in enhancing the comprehension of pressure sinkage and bearing capacity in soil mechanics. Extensive research is required to comprehensively hold the multitude of factors affecting the mobility of tracked vehicles across diverse terrains and conditions.

Tracked vehicles have proven superior performers in off-road environments, owing to their unique design advantages compared to conventional wheeled vehicles[24]. Their substantial ground contact area offers remarkable stability in challenging terrains, resulting in even weight distribution. Rubber tracks have further augmented these vehicles, promising exceptional traction and optimized ground pressure. Nevertheless, despite these advancements, a significant research limitation remains in understanding how tracked vehicles behave on various soil types.

An essential aspect of this challenge involves the complex interplay of mechanical properties between the vehicle and the terrain. Soil, in all its diverse forms—moisture-rich Bentonite or granular Diatom—presents distinct challenges to vehicle mobility. Concerns arise regarding the interaction between the weight of a tracked vehicle and the moisture content of the soil, as well as the way its mechanical treads contact the granular structure of the soil. Researchers have tackled these questions using tools like soil bins for controlled experiments, delving into pressure sinkage and bearing capacity [9,27–30]. However, while these findings have been groundbreaking, they have often been restricted by laboratory settings, highlighting the need for real-time validations.

The performance and mobility of vehicles greatly depend on their interaction with the terrain they traverse[29]. Terrain mechanical characteristics include two key aspects: the expected pressure-sinkage relationship and the tangential shear load versus slippage dynamics. While classical models,

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such as those proposed by M.G. Bekker [25] and Reece [7], have aimed to capture these interactions, they often fall short in replicating real-world scenarios, incredibly when overlooking critical factors like soil moisture content. Traditional thermomechanical models, while pioneering, sometimes struggle to accurately simulate the intricate relationship between vehicle tracks and various soil types, mainly when variables like soil moisture and loading conditions come into play [8,29].

In order to bridge this gap, our study aims to navigate this complex terrain by presenting an improved design that combines the foundational principles of established models with insights from contemporary research. This study analyzes the connection between tracked vehicles and terrains. Through experiments conducted on custom test tracks and in-depth analysis, the aim is to address existing gaps in Terramechanics research and provide valuable insights to inform future considerations, criteria for rubber-track vehicles, challenges encountered in their development, pressure sensor implementation, and studies on soil bed terrains.

In addition, the study of soil behavior holds immense significance in various fields, including geotechnical engineering, agriculture, and environmental science. A comprehensive understanding of how soils interact with varying moisture levels is essential for predicting ground stability, assessing sinkage performance, and evaluating environmental impacts. This research introduces an innovative approach to conducting controlled tests on Bentonite and Diatom soil mixed with sand and gravel, focusing on monitoring pressure sinkage using a specially designed rigid rubber-tracked vehicle.

2. Materials and Methods

2.1. Tools and Sensors

Tools and sensors are essential components that assist in controlled environment soil bin tests to get accurate data regarding various associated variables. Different tools and sensors are included in the whole apparatus setup for the experiment, as shown in Table 1 and Figure 1. To gather accurate and detailed information about the vehicle's interaction with several terrains, a pressure sensor known as the ZNHM-D1-2T-22121401 model is utilized. This sensor works with a voltage range of 5-15V DC, can measure pressures of up to 214.5 kPa/214500 N/m2, and is incredibly accurate, with a precision of 99.9%. To monitor soil moisture levels, the JXBS-3001-TR_4G moisture and temperature sensor was used (illustrated in Supplementary Figure S5. Soil moisture sensors' real-time data monitoring web-based interface tool shows temperature, humidity, and signal strength.

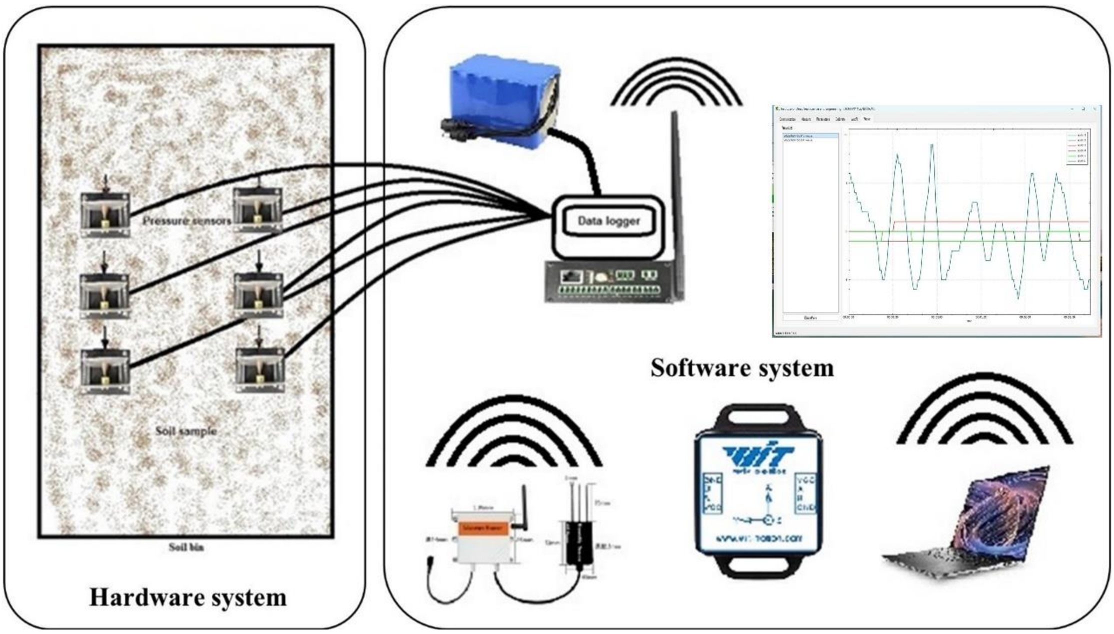

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Figure 1. Schematic drawing of the model experiment (soil bin, pressure sensors, wireless data logger equipment, signal amplifier, 12V/24V power supply, the 9-axis attitude sensor, communication module, and software).

Table 1. Overview of apparatuses used and measurement instrumentations

Items	Model	Operating voltage	Measuring range	Measurement accuracy
Pressure sensor	ZNHM-D1-2T-22121401	5-15V DC	214.5kPa -40 to 85°C	99.9% ±0.5% FS
Moisture sensor	JXBS-3001-TR_4G	12-24V DC	0-100% -40 °C-80 °C	3% in the range of 0-53% 5% in the range of 53-100%
Cone Penetrometer	SC 900	4 AAA alkaline batteries	0 - 18″ (0 - 45 cm) 0 – 1000 PSI (0 - 7000 kPa)	±0.5″ (±1.25 cm) ±15 PSI (±103 kPa)
Data logger built-in Wireless serial communication module	FD0843 (6 Channel)	9~24V DC, <10W	100/200/400/800/1600	Temp: -30°~ 65℃ Relative humidity: 10%~ 95% A/D Update rate: 1600Hz Data transfer rate:100Mb/s
Direct Shear Apparatus	ZJ-1B	110-240V AC	Shear Displacement: 0-50 mm Normal Load: 0-400 kN	Shear Displacement: ±0.01 mm Normal Load: ±0.5% of applied load Shear Load: ±0.5% of measured value
9-axis attitude sensor	WT901BLECL5.0	3.7V – 260mah	TCP: 1~10Hz UDP: 1~200Hz	Angular accuracy X, Y axis 0.2°, Z axis 1°

Supplementary Figure S6. (a) presents a 4G wireless soil temperature and moisture sensor, and Supplementary Figure S6. (b) shows a wireless communication module. This sensor operates with 12-24V DC and can measure moisture levels from 0-100% over a temperature range of -40 °C to 80 °C and provides accurate readings, with a 3% margin of error for moisture levels between 0-53% and a 5% margin of error for moisture levels between 53-100%. To assess soil compaction, the SC-900 Cone Penetrometer was used, which is powered by four AAA alkaline batteries and can measure depths from 0-18″ (0-45 cm) and pressures from 0-1000 PSI (0-7000 kPa). It has a depth accuracy of ±0.5″ (±1.25 cm) and a pressure accuracy of ±15 PSI (±103 kPa).

Data collection was managed using the FD0843 data logger, which features a wireless serial communication module that operates on 9~24V DC power and consumes less than 10W. This device can handle various A/D update rates, with the capability to go up to 1600 Hz. In addition, the design allows it to operate in high temperatures ranging from -30° to 65 ℃ and relative humidity levels of 10% to 95%, with the data transfer rate for this logger being 100 Mb/s. The WT901BLECL5.0 sensor model was utilized to capture vehicle orientation data. This sensor operates on 3.7V with a 260 mAh battery and can transmit data at different rates, with an angular accuracy of 0.20 for the X and Y axes and 10 for the Z axis. More details about the sensor and data logger are given in supplementary (Supplementary Figure S7) sections, and the data logger's detailed specifications are illustrated in Supplementary Table S1.

Figure 1. displays a detailed schematic diagram of the experimental model setup, showing the essential components and their connection. The experiment is carried out in a controlled dirt bin environment. The key components consist of pressure sensors strategically positioned within the soil container to detect fluctuations in ground pressure. The sensors are linked to a wireless data recorder, enabling immediate data collection.

The signal amplifier boosts the sensor signals, guaranteeing precise and dependable measurements. The system is powered by a 12V/24V power source, which supplies the required

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electrical energy. A 9-axis attitude sensor enhances the ability to monitor the vehicle's orientation and tilt during the experiment.

A communication module facilitates uninterrupted data transmission among the sensors, data logger, and external devices. The complete experimental arrangement is coordinated and supervised using specialized software, which offers a user-friendly interface for visualizing, analyzing, and interpreting data.

This schematic diagram provides a straightforward and precise summary of the experimental setup, highlighting the incorporation of different components necessary for an organized and regulated evaluation of ground pressure, bearing capacity, and sinkage in rigid-flexible tracked vehicles on specific terrains.

2.2. Experimental Procedure

This study uses a specially designed small rigid rubber-tracked vehicle to monitor pressure sinkage in cohesion soils such as Bentonite and Diatom, especially when mixed with sand and gravel. Creating a prototype vehicle for conducting pressure sinkage experiments in a soil bin involves carefully considering various critical factors. This vehicle utilizes rubber tracks to minimize surface disturbance and ensure adequate traction on the soil. The narrower track dimensions are chosen based on the soil types' unique characteristics. These narrower rubber tracks enhance penetration in cohesive soils like Bentonite and Diatom mixed with sand and gravel, improving the monitoring process. We selected a rubber-based flexible tracked vehicle for our experiments, suitable for various applications—the vehicle measured 120 cm in length, 90 cm in width, and 80 cm in height, has a 90 cm contact length of rubber track, 20 cm width of single rubber track, illustrated in Figure 2, and Table 2 presents the fundamental parameters of the experiment utilizing a tracked vehicle.

Table 2. A tracked vehicle was used for the experiment's basic parameters.

Parameter name	Symbol	Parameter content
Track length × width × Height (cm)	$L_x \times L_y \times L_z$	120 × 90 × 80
Contact length of rubber track	cm	90
Width of single rubber track	cm	20
Drive wheel diameter	cm	26
Front idler diameter	cm	32
Lugs	cm	19
Weight of the tracked vehicle	W (kg)	544
Weight of the vehicle in the water	W_w (kg)	523.25
Contact Pressure	P (kPa)	13.889
Contact Pressure in the water	P_w (kPa)	12.5

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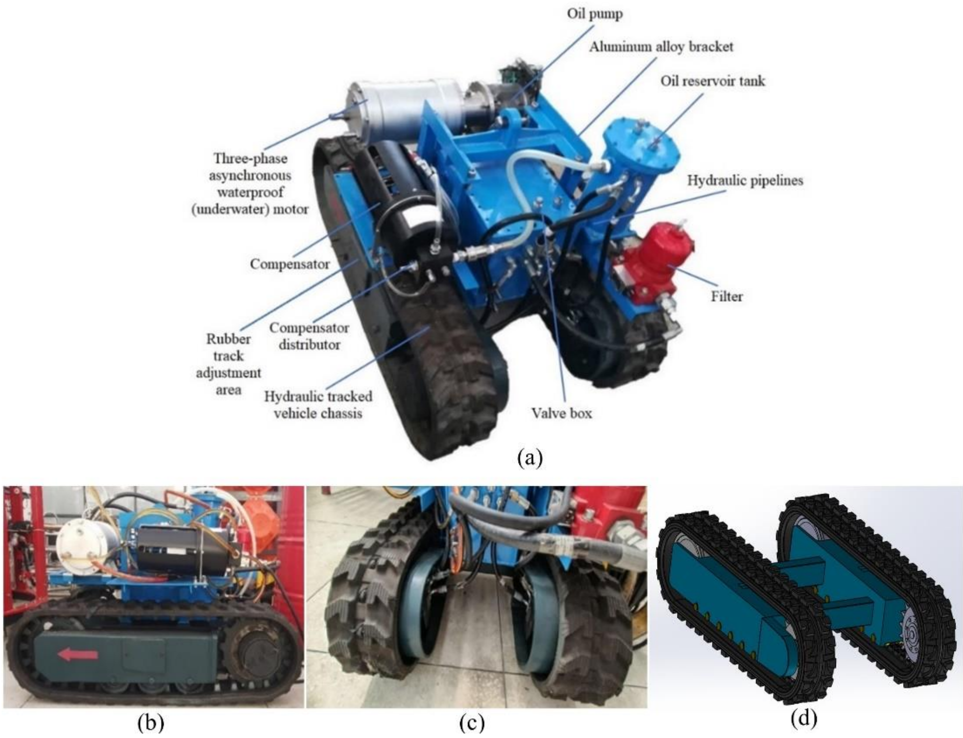

Figure 2. (a) Image of bodies of a mini rigid tracked vehicle; (b) Proposed tracked vehicle's side view; (c) Proposed tracked vehicle's front view; (d) Solidworks schematic track diagram.

The vehicle's compact size allows it to navigate within the limited space of the soil bin while minimizing soil disturbance, ensuring stable and even weight distribution to avoid affecting pressure sinkage measurements. The rubber-tracked vehicle is designed to distribute its load evenly across the tracks, preventing localized pressure points and ensuring sufficient traction for effective movement on the soil surface. The track system is optimized with durable and wear-resistant materials suitable for specific soil conditions, including Bentonite and Diatom soil mixed with sand and gravel. The study involved a comprehensive examination of soil sampling techniques, encompassing the selection of soil combinations such as Bentonite, Diatom, sand, and gravel. Precise gravimetric methods were employed to maintain consistent moisture levels within predetermined ranges, ensuring the reproducibility of experiments. These experiments occurred within an indoor soil bin at the Institute of Deep-Sea Science and Engineering (IDSSE) of the Chinese Academy of Sciences. Measuring ground pressure within the 610 cm x 245 cm x 180 cm soil bin while the uncrewed tracked vehicle was in motion posed distinctive challenges.

The mixture composition used in the experiment played a crucial role in simulating real-world soil conditions within the soil bin. The carefully crafted blend consisted of specific proportions to mirror natural terrains encountered by off-road rubber-tracked vehicles. The sand gravel mixture comprised 17% sand, providing granularity and texture to the soil, 13% gravel (2-5 mm) for added coarseness and variation, and the majority, 70%, consisted of a combination of Diatom or Bentonite sedimental soil.

Diatom or Bentonite soil in the sand gravel mixture aimed to replicate the complexities of real-world sea sediment soil compositions. Diatom soil, known for its unique properties and often found in layered formations (microscopic algae with siliceous cell walls), possesses unique properties that influence the overall behavior of the soil mixture[31,32]. Diatomaceous earth is known for its lightweight and porous nature, providing a specific texture to the soil. Including Diatom soil in the mixture introduced varying degrees of porosity and permeability, affecting parameters such as water retention and drainage.

On the other hand, Bentonite soil, a type of clay with high plasticity and swelling characteristics, contributed to the cohesive and adhesive properties of the mixture [33,34]. Bentonite can absorb water and undergo volumetric changes, influencing the soil's overall moisture content and structural

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stability. Bentonite's cohesive nature can impact the soil's sinkage, pressure distribution, and bearing capacity under the rubber-tracked vehicle's applied load.

The addition of sand and gravel further diversified the soil composition. Sand, with its granular structure, influenced the overall texture and cohesiveness of the mixture. Gravel, characterized by larger particles, introduced heterogeneity and potential challenges for the rubber-tracked vehicle, simulating the presence of coarse elements in natural terrains.

The 17% sand content contributed to the overall stability of the mixture, influencing factors such as cohesion and friction between soil particles. The 13% gravel, with particle sizes ranging from 2 to 5 mm, introduced additional heterogeneity, mimicking the presence of small rocks or coarse elements in natural terrains. This variation in particle sizes within the gravel component could impact the soil's overall mechanical behavior under the rubber-tracked vehicle's influence.

By carefully combining Diatom/Bentonite, sand, and gravel in the specified proportions, the soil profile created in the soil bin aimed to challenge the rubber-tracked vehicle across various aspects. The experiment examined how the vehicle interacted with this complex mixture, focusing on sinkage, pressure distribution, and bearing capacity. This approach provided valuable insights into the performance of off-road vehicles in challenging sea sediment soil conditions. The composition was to facilitate a comprehensive investigation into soils' sinkage pressure and bearing capacity, especially when subjected to the traversal of a rubber-tracked vehicle. Including Diatom/Bentonite soil and sand and gravel allowed for a nuanced exploration of the interaction dynamics between the vehicle and diverse soil types in a soil bin-controlled experimental setup.

After each trial, the soil was meticulously prepared by tilling, leveling, and compacting. Cone penetration tests (CPT) were utilized to evaluate soil resistance and compaction at different depths and moisture levels, as illustrated in Table 3. The paper also delves into the setup and instrumentation configuration of the test stand, including the strategic placement of sensors for pressure measurements. A sophisticated data logger was utilized to record ground sinkage pressure data, enhancing the study's capacity for replication and practical application.

Table 3. Cone penetration resistance at different moistures.

Soil	Depth (cm)	Cone penetration resistance kPa @ Moisture (± %)		
		10 ± %	**20 ± %**	**30 ± %**
Bentonite	0-5	10 kPa	20 kPa	40 kPa
	5-15	15 kPa	30 kPa	45 kPa
	15-30	20 kPa	25 kPa	50 kPa
Diatom	0-5	15 kPa	18 kPa	20 kPa
	5-15	18 kPa	20 kPa	22 kPa
	15-30	20 kPa	22 kPa	25 kPa

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Figure 3. Experimental setup for Soil Bin and pressure sensor installation location(a) Soil Bin used for the experiment, (b) Diatom soil in soil bin, (c) Bentonite soil in soil bin, (d) Sand gravel mixture mixed with bentonite soil, (e) Tracked vehicle and pressure sensor installation location, (f) front, mid, and Rear pressure sensor location in soil bin.

Figure 4. Cone penetrometer and sampling by cone penetrometer.

A significant quantity of Bentonite, Diatom, sand, and gravel (ranging from 2mm to 5mm) was initially obtained. The mixture comprised approximately 16 to 19% sand, 11 to 16% gravel, and 70% Diatom/Bentonite soil. Both Bentonite and Diatom were dried in the sunlight until they became loose powder, making it possible to adjust their moisture content later. This dried soil was then transported to the soil bin and added layer by layer in 5 cm increments, evenly distributed using a small wooden roller and hand shovel. The parameters for the soil bin used in the pressure sinkage and bearing capacity experiments are, and the detailed parameters for the soil bin used in the pressure sinkage experiment are shown in Supplementary Table S6. Soil deposition continued until the depth reached 40 cm in the bin.

A calculated amount of water was added, and the standard gravimetric technique was used to determine moisture content by comparing wet and dry weights. This process ensured uniformity and brought moisture levels within specified ranges (approximately 9 to 13%, 18 to 23%, and 29 to 33%)

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for both Bentonite and Diatom soil. The amount of water needed for each moisture level was determined using real-time data from a wireless moisture sensor (shown in Supplementary Figure S4). A systematic approach was employed to maintain the desired moisture levels in the soil bin, involving adding water and continuous monitoring throughout the experiment. This process was crucial for controlling the moisture content, a parameter that significantly influences the behavior of the rubber-tracked vehicle in the soil. The addition of water to the soil mixture was carried out meticulously to ensure even distribution and saturation. This step was executed gradually to prevent abrupt changes in soil properties and maintain the uniformity of the experimental conditions.

A vital component of the moisture management strategy was the integration of moisture sensors within the soil bin. These sensors provided real-time data on the moisture levels in the soil, offering continuous insights into the evolving conditions. The research team utilized this data to make informed decisions regarding adjustments to water content, ensuring that the moisture levels remained within the targeted range.

The monitoring process extended beyond water addition; the team implemented environmental controls to mitigate external factors that could affect moisture levels. These controls helped minimize evaporation and external fluctuations, contributing to the stability of the experimental conditions.

To maintain desired moisture levels, a wireless moisture sensor continuously monitored soil moisture in real-time, allowing for precise adjustments in water content. This careful monitoring and adjustment ensured that the soil samples remained within the specified moisture content ranges throughout the experiment.

After mixing with water, the soil was left in the bin to settle for 24 hours. Separate containers were used for each moisture level within each soil type to control moisture content accurately. The soil bin was assigned distinct moisture ranges for targeted analysis and regulation of soil behavior under varying moisture levels for both Bentonite and Diatom soil samples. Supplementary Figure S5 illustrates an online moisture sensor that monitors real-time temperature, soil moisture, and signal intensity.

The testing bin, measuring 610 cm x 245 cm x 180 cm and reinforced with steel sheets and bars, was constructed to withstand the applied loads and prevent soil leakage, as illustrated in Supplementary Figure S2. Before initiating the experiments, a geomembrane liner was used to prevent moisture evaporation, and a layer of drainage gravel was added for proper drainage. The sand-gravel mixture was carefully added to the bin in layers approximately 30 cm thick. In order to ensure uniform compaction, the surface was prepared by removing debris, large stones, and potential obstructions that could hinder the process. The bin underwent thorough inspection and cleaning before the placement and compaction of soils, creating a well-defined workspace conducive to achieving uniform soil compaction. After confirming even distribution and slight soil dampness, the surface was allowed to settle for 24 hours before the experiments began. Following each trial, the soil was manually loosened using a hand shovel. A moisture sensor was embedded horizontally within the compacted Bentonite/Diatom soil layer to monitor any fluctuations during the experiments. These sensors were wirelessly connected to a data logger for real-time monitoring. Each test was repeated three times to account for any inconsistencies arising from the random non-uniformity of the soil samples.

2.3. Soil Path Setup and Experimentation

A specific path within the soil bin was designated for soil compaction and testing. Before adding soil to the bin, the base was carefully leveled using a mixture of sand and gravel to ensure a consistent and sturdy foundation. This step aimed to remove potential obstacles and establish a uniform surface for compaction and testing. The mechanical properties of Bentonite and Diatom soils used in the experiment are outlined in Supplementary Table S2. In contrast, loose and compact soil properties for the tracked vehicle soil bin experiment are detailed in Supplementary Table S3 and S4. Detailed soil properties, including soil particle density, natural moisture content, grain size distribution, maximum dry density, and the optimum moisture content for the Bentonite, Diatom, and sand gravel mixture, are illustrated in Supplementary Table S7.

Pressure sensors enclosed in brackets containing moisture sensors were placed within the bin and connected to a wireless data-collection system to collect essential data during testing. This setup allowed continuous monitoring of pressure distribution and moisture fluctuations in the soil, providing valuable insights into the soil's behavior under external forces. The careful arrangement and equipment used in the soil bin ensured accurate and thorough experimentation, generating valuable data for analysis and interpretation. This methodology has significantly improved our understanding of how soil behaves under various load conditions, contributing to soil mechanics and geotechnical engineering.

The laboratory-controlled experiments conducted a calibration procedure to ensure the accuracy of pressure measurements and validate the vehicle's response to varying moisture levels. The design allowed easy access to the soil bin for experimental setup, equipment maintenance, and data collection. The soil bin experiment and vehicle design included safety topographies such as guards, emergency stop buttons, and operational protections. The collected pressure sinkage data from the vehicle's sensors were analyzed to assess the behavior of Bentonite and Diatom soil mixed with sand and gravel under different moisture conditions.

The rubber-tracked vehicle was positioned at one end of the soil bin and driven at speeds ranging from 0.1 to 0.3 m/sec motion test on Diatom and Bentonite Soil at loose and compacted soil density along a predetermined path as outlined in Supplementary Table S8. Parameters like sinkage, vehicle speed, and pass count were carefully recorded during these tests. This testing process was repeated at various speeds to gain a better understanding of soil behavior, including the physical properties of the Bentonite, Diatom, and Sand-Gravel mixture under different loading conditions, as shown in Supplementary Table S5. Upon completing the tests, data was analyzed to comprehend pressure distribution and its relationship with sinkage, soil-bearing capacity, vehicle speed, and moisture content. It is worth noting that test procedures may vary depending on the particular goals of the pressure sinkage test, the type of soil, and the specific tracked vehicle used.

The rubber-tracked vehicle recorded multiple parameters during the pressure sinkage test on the Bentonite/Diatom terrain. These parameters included contact pressure, sinkage, soil moisture content, and vehicle speed. Pressure sensors placed within the bin were calibrated and synchronized with a data logger to capture real-time data. Before the main tests, a dry run was conducted to ensure sensor functionality and to habituate the operator with the terrain and path. Given its significant impact on sinkage and pressure distribution, soil moisture levels were regularly checked using a moisture meter. As the vehicle traversed the terrain, sensors recorded data on the pressure exerted by the tracks, and sinkage was measured either using displacement sensors or visually observed based on side bin markings. Additional parameters such as load, inclination, and vehicle speed were assessed. An attitude sensor with 9-axis monitoring capability was used to track the vehicle's speed and trajectory within the bin, as shown in Supplementary Figure S3.

After the experiments, the collected data was applied for external validation to establish pressure-sinkage relationships. Graphs showing the sinkage versus pressure for Bentonite and Diatom soil were generated using Python. A comprehensive overview of the experimental setup, including the soil bin, track vehicle, pressure sensors, data acquisition system, and data analysis methods, is provided in Figure 5, which illustrates the key components of the experimental configuration, outlining the process for collecting data and analyzing it to gain meaningful insights into ground pressure, bearing capacity, and sinkage in rigid-flexible tracked vehicles.

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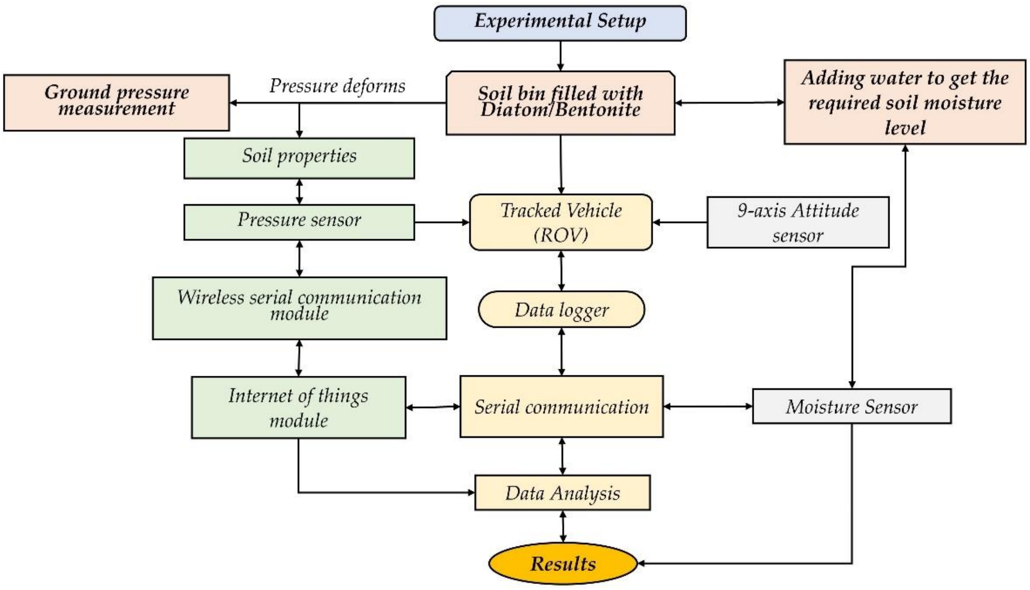

Figure 5. Flow diagram of complete ground instrumentation system for pressure sinkage measurement experiment.

2.4 Pressure Sensors and Brackets

Pressure sensors are commonly used in various applications, including in underwater environments, and play a fundamental role in track-soil interaction studies by providing essential data to measure the distribution and magnitude of pressure exerted by tracked vehicles on the soil surface. These sensors are instrumental in understanding the mechanical behavior of the soil when subjected to the weight and movement of the vehicle. The data gathered from pressure sensors enables researchers to analyze how the ground pressure is distributed and how it varies over time. In underwater vehicles, such as Remotely Operated Vehicles (ROVs), pressure sensors are utilized in track soil interaction studies to measure the distribution and magnitude of pressure the tracked vehicle exerts on the soil surface. These sensors provide crucial data to understand the mechanical behavior of the soil under the influence of the vehicle's weight and movement. Table 1 illustrates the detailed parameters of the ZNHM-D1-2T-22121401 pressure sensor used in the experiment.

The importance of pressure sensors in rubber-track soil interaction studies lies in their ability to capture actual pressure variations. This real-time data collection is crucial as it enables researchers to observe how the vehicle's weight is distributed across the soil surface and how this distribution changes as the vehicle moves. By capturing static and dynamic pressure changes, pressure sensors provide insights into the localized stresses applied to the soil, allowing for a detailed analysis of the interaction between the vehicle and the soil. Moreover, pressure sensors contribute to establishing a comprehensive understanding of the ground pressure distribution beneath the tracked vehicle. This information is valuable for evaluating how different types of soil and varying moisture levels may impact the pressure exerted by the vehicle. By studying the ground pressure distribution, researchers can gain insights into the soil's load-bearing capacity and its deformation characteristics under the influence of the vehicle.

Additionally, pressure sensors enable the measurement of pressure sinkage, which refers to the depth to which an object, in this case, the track of the vehicle, penetrates the soil under the applied pressure. This data is significant for assessing the soil's resistance to penetration and the vehicle's ability to traverse different soil types and conditions.

Supplementary Figure S1 shows that the purpose of the sensor bracket is to hold the pressure sensors in place securely and keep them aligned and safe from haphazard, ensuring accurate and consistent measurements during the interaction between the tracked vehicle and the soil. These brackets are typically made of aluminum or stainless steel, which are corrosion-resistant and can help absorb impacts from debris and protect the pressure sensor from damage. The frames can be attached

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to the soil bin or vehicle using bolts, clamps, or other fastening methods. The sensor bracket can enclose the pressure sensor, creating a protective barrier around it, thus preventing debris from contacting the sensor and potentially damaging it. It also serves to maintain the alignment and positioning of the pressure sensors, preventing displacement or disturbances that could compromise the reliability of the collected data. This allows for precise monitoring of pressure variations at specific locations, contributing to a comprehensive understanding of the impact of the tracked vehicle on the soil surface.

2.5 Safety Protocols

Stringent safety protocols were consistently followed during the experiments to ensure the safety of contributors and minimize potential hazards. These safety measures included using personal protective equipment (PPE), hazard identification, emergency response planning, and compliance with established safety guidelines and regulations. These measures were crucial in creating a safe and controlled experiment environment, reducing the risk of accidents or unexpected incidents. In addition to prioritizing safety, the experimental data collected was subjected to careful analysis, interpretation, and review using a rigorous and systematic methodology. This comprehensive analysis considered various parameters, including soil-bearing capacity, compaction behavior, shear strength, and deformation characteristics. The outcomes provided a deep understanding of how the soil responds under different experimental conditions, offering valuable insights applicable to various engineering applications, such as predicting vehicle mobility, foundation design, and construction procedures. A comprehensive understanding of soil behavior under varying conditions was achieved by constantly adhering to safety protocols and conducting thorough analyses of experimental data.

3. Results and discussion

3.1. Track Vehicle and Sinkage Observations

This study analyzed the effects of varying soil moisture levels on the sinkage of a tracked vehicle moving at a constant speed of 0.1 m/s across two soil types, Bentonite and Diatom (illustrated in Table 4). As the moisture content increased from 5% to 30% for Bentonite, there was a notable progression in sinkage, from 1.10 cm with normal track wear at 5% to a significant 3.80 cm with increased track slippage at 30%. This progression in Bentonite sinkage, especially at increased moisture levels, resonates with prior findings that heightened water content tends to soften soil aggregates and the bond between them, leading to increased compressibility, particularly at lower vertical stresses [35,36]. The consequence of this condition is evident in the severe rutting and track deformation observed starting at 20% moisture content in the current study. On the other hand, the Diatom soil exhibited a different tendency. At 5% moisture, sinkage was a modest 0.55 cm with regular wear on the tracks. As the moisture content ramped to 30%, the peak sinkage was 1.30 cm, marked by profound track deformation and sinking.

Table 4. Vehicle Pressure Sinkage Test Observations @ 0.1m/sec velocity.

Soil	Moisture (%)	Speed (m/s)	Sinkage (cm)	Track-Soil Observations
Bentonite	5	0.1	1.10	Normal wear and tear on tracks
Bentonite	10	0.1	1.50	Rutting beginning tracks deforming
Bentonite	15	0.1	2.40	Deep rutting, tracks digging in
Bentonite	20	0.1	2.70	Severe rutting, tracks stuck
Bentonite	25	0.1	3.20	Severe track deformation and sinking
Bentonite	30	0.1	3.80	Increased track slippage
Diatom	5	0.1	0.55	Normal wear and tear on tracks
Diatom	10	0.1	0.80	Minor rutting
Diatom	15	0.1	0.83	Rutting

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Diatom	20	0.1	0.90	Deep Rutting
Diatom	25	0.1	1.21	very soft soil, tracks dug in
Diatom	30	0.1	1.30	Severe track deformation and sinking

This disparity in the response of the two soils indicates that the tracked vehicle confronted more formidable challenges on Bentonite, especially at elevated moisture levels, than on the Diatom soil under analogous conditions. The shift in hydraulic conductivity with moisture, which affects soil permeability, might provide an added layer of explanation for the marked sinkage and deformation at high moisture levels, drawing parallels with observations from Cuisinier et al. [37] and Wang et al. [38], making navigation more taxing for the vehicle. The presented track-soil data holds significance as it facilitates a comprehensive understanding of the interplay between vehicle tracks and soil under varying moisture conditions. Through analyzing vehicle tracks on the soil surface, researchers and engineers can gain valuable information into its response to variable moisture levels. The above data has significant potential for utilization in various industries, including mining, construction, agriculture, and geotechnical engineering.

3.2. Soil behavior

The experiment placed significant emphasis on examining the behavior of soil, particularly Bentonite, Diatom, and sand gravel mixture illustrated in Figure 6. when subjected to a load of a tracked vehicle focusing on several metrics, including loose density, compacted density, compaction percentage, depth, and cone index measurement for Bentonite and Diatom which is illustrated in Supplementary Table S9, and graphically representation in Figure 7a–c. It is imperative to comprehend the reaction of these soils to the weight and motion of the vehicle to evaluate their compaction, load-bearing capability, and deformation properties. The term "sinkage behavior" pertains to the extent of soil penetration by vehicle tracks during their terrain traversal. The objective of this study was to monitor and analyze the sinkage behavior of Bentonite and Diatom soil under varying situations. The information provides valuable insights into the soil's capacity to withstand external loads and compaction properties.

Figure 6. (a) Bentonite clay (-0.063mm), (b) Diatom soils (>20μm), and (c) Sand-gravel mixture (2mm~5mm) were used in the experiment.

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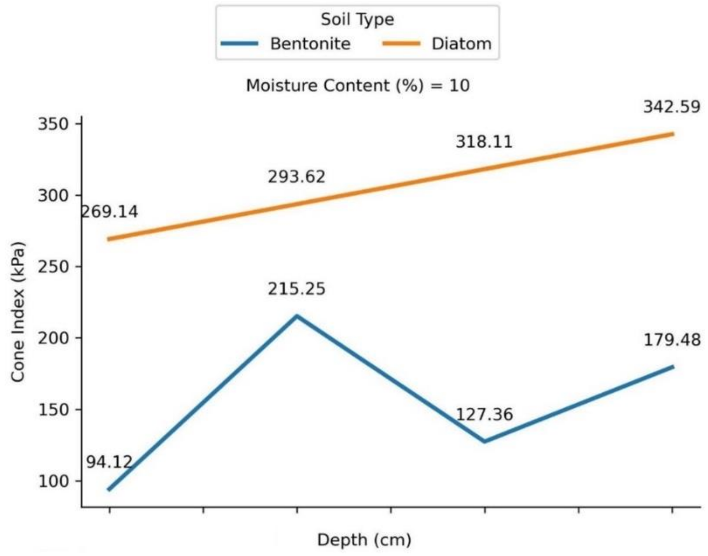

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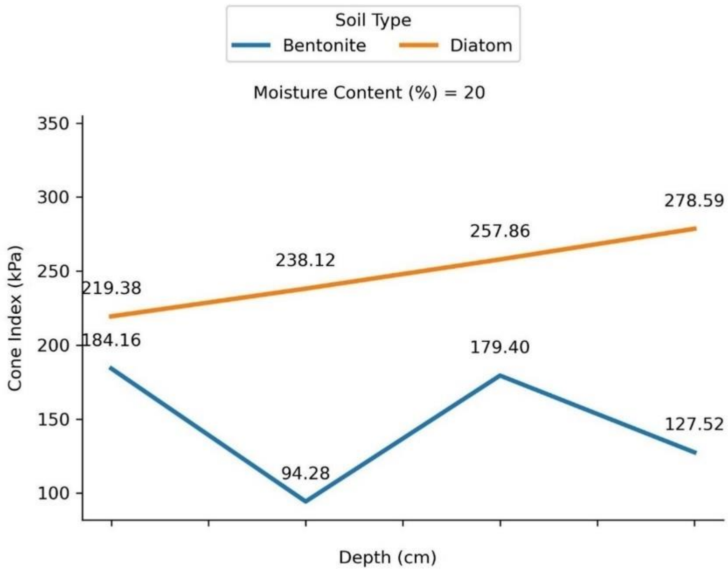

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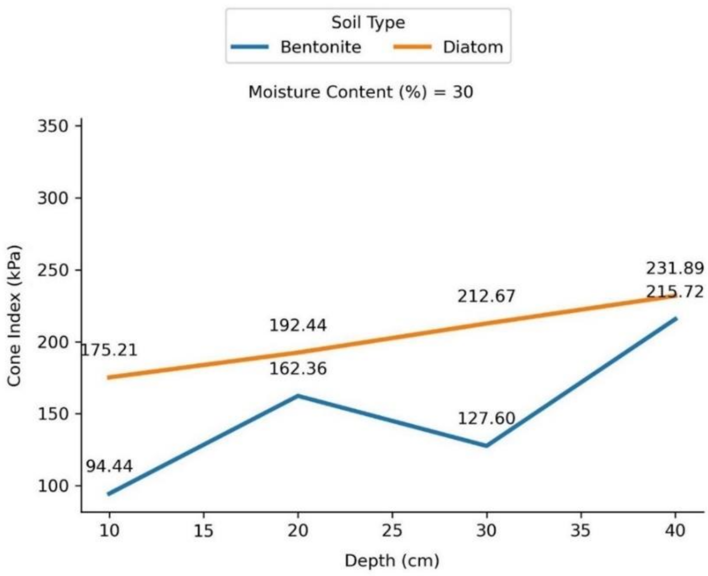

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Figure 7. (a). Bentonite and Diatom's Cone Index, at 10% Moisture Content and Penetration Depth. **(b).** Bentonite and Diatom's Cone Index, at 20% Moisture Content and Penetration Depth. **(c).** Bentonite and Diatom's Cone Index, at 30% Moisture Content and Penetration Depth.

Figure 7a compares the Cone Index of Bentonite and Diatom soils at 10% moisture. The graphic shows the link between penetration depth and the Cone Index, revealing the soil's mechanical strength in this moisture condition. The data helps us understand soil behavior, particularly their ability to carry weights and resist penetration under controlled conditions.

Figure 7b comprehensively evaluates the Cone Index for Bentonite and Diatom soils at a moisture content of 20%. The map graphically illustrates the correlation between the penetration depth and the appropriate Cone Index values, offering a complete overview of the mechanical properties of the soils at this particular moisture level.

Figure 7c clarifies the complex connection between soil behavior, moisture content, and penetration resistance. This graph examines explicitly the Cone Index values of Bentonite and Diatom soils under a moisture content of 30%. It comprehensively depicts how these soils react to penetration at different depths. The plotted data visually illustrates the relationship between Cone Index values and penetration depth, offering crucial insights into the soil's load-bearing capability and mechanical properties. When the moisture level reaches 30%, the Cone Index becomes vital in determining the soil's resistance to penetration. This characteristic affords valuable information about the suitability of the soil for different applications.

When a tracked vehicle exerts pressure on the soil surface, it initiates a process where the soil particles undergo rearrangement and compaction. Several elements, such as the kind of soil, the amount of moisture present, and the intensity of the applied load, influence the compaction behavior of the soil. By closely observing the sinkage behavior, we gain valuable insights into the compaction characteristics of both Bentonite and Diatom soil when subjected to the weight of the tracked vehicle.

In the case of Bentonite soil with a moisture content of 10%, we observed two distinct density values: a loose density of 1.3 g/cm^3 and a compacted density of 1.5 g/cm^3. It resulted in a compaction percentage of 15.38%. This level of compaction can be attributed to the inherent response of the soil to stress, a phenomenon highlighted by Alaoui and Helbling [39]. Their research also emphasized the structural collapse of soil due to compaction at similar depths. Specifically, the cone index values presented noticeable variability at this moisture level: 94.12 kPa at 10 cm, soaring to 215.25 kPa at 20 cm, then decreasing to 127.36 kPa at 30 cm, and again increasing to 179.48 kPa at 40 cm. As the moisture content for Bentonite increased to 20%, the loose density reduced slightly to 1.2 g/cm^3 and the compacted density to 1.4 g/cm^3.

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However, intriguingly, the compaction percentage rose to 17.67%. Zhang et al. [40], in their observations on the impact of tractor movement on soil compaction, might shed some light on this. They found increased soil bulk density with enhanced tractor movement, hinting at the likelihood of a similar relationship between moisture content and compaction in Bentonite. In this moisture setting, the cone index exhibited a pattern, starting with an initial spike to 184.16 kPa at 10 cm depth, then a reduction to 94.28 kPa at 20 cm, before alternating between 179.4 kPa at 30 cm and 127.52 kPa at 40 cm. At the apex moisture content of 30% for Bentonite, a decline in the loose and compacted densities d to 1.1 g/cm³ and 1.3 g/cm³, respectively, was observed. This was coupled with a compaction percentage of 18.18%, suggesting even more pronounced effects of moisture on soil's structural integrity. The cone index at this moisture level shows a diverse landscape, displaying values of 94.44 kPa, 162.36 kPa, 127.6 kPa, and 215.72 kPa for depths of 10 cm, 20 cm, 30 cm, and 40 cm, respectively. The study assessed load-bearing capacity and deformation characteristics of Bentonite and Diatom soil under a rubber-tracked vehicle, offering insights for engineering applications.

The soil exhibited increased sinkage and compaction with higher moisture content, impacting its load-bearing capacity. Diatom soil, unlike Bentonite, shows distinct reactions to moisture variations. At 10% moisture, the densities suggest a 22.29% compaction, potentially influenced by Diatom's unique properties. The consistent cone index progression from 269.14 kPa at 10 cm to 342.59 kPa at 40 cm signifies a growing resistance with depth, possibly due to overlying soil pressures. As moisture rises to 20%, densities drop, but compaction grows to 25.4%. This could be attributed to water-soil particle dynamics affecting particle arrangement, a phenomenon aligning with Alaoui and Helbling [39], where compaction restricted water movement. The increasing cone index from 219.38 kPa to 278.59 kPa can be related to increased resistance from soil layer pressures or decreased porosity, as Samuel and Ajav [41] observed. At 30% moisture, despite lower densities, there is a peak compaction of 28.57%. This tighter packing, coupled with the rise of the cone index, resonates with findings from Zhang et al. [40] and Botta et al. [42], indicating similarities between mechanical impact and moisture's effect on soil.

3.3. Ground Pressure and Sinkage Test Results

Ground pressure, quantifying the force exerted by the track car on the ground, was measured using high-precision sensors. Sinkage data provided insights into soil load-bearing capacity and compaction behavior across varying moisture and soil conditions. In dense Diatom soil, higher ground pressure led to increased sinkage, indicating limited load-bearing capacity, while loose Diatom soil exhibited lower ground pressure and reduced sinkage. As vehicle weight increased, ground pressure and sinkage rose, but the even weight distribution of rubber tracks mitigated excessive sinkage.

The behavior of the rubber-tracked vehicle's pressure sinkage, ground pressure, and speed test on Bentonite and Diatom can be observed in Figure 8a–c. The comprehensive data is included in Table 5, providing substantial insights into its reaction to various speed and moisture conditions. At a relatively lower speed of 0.1 m/s, as moisture content increases, there is an apparent linear increase in ground pressure from 23 kPa to 27 kPa. The linearity suggests that moisture content directly influences the mechanical properties of Bentonite, potentially affecting its cohesive and adhesive characteristics.

Comparatively, a past study by Mishra et al. [43] observed a slightly lower range, suggesting a different mechanical response to moisture. This progression in pressure is mirrored in the sinkage values, which grow from 1.5 cm to 3.8 cm. One could posit that at this speed, the moisture aids in binding the Bentonite soil particles, thereby increasing the resistance to external pressures, a phenomenon also supported by the rise in sinkage values.

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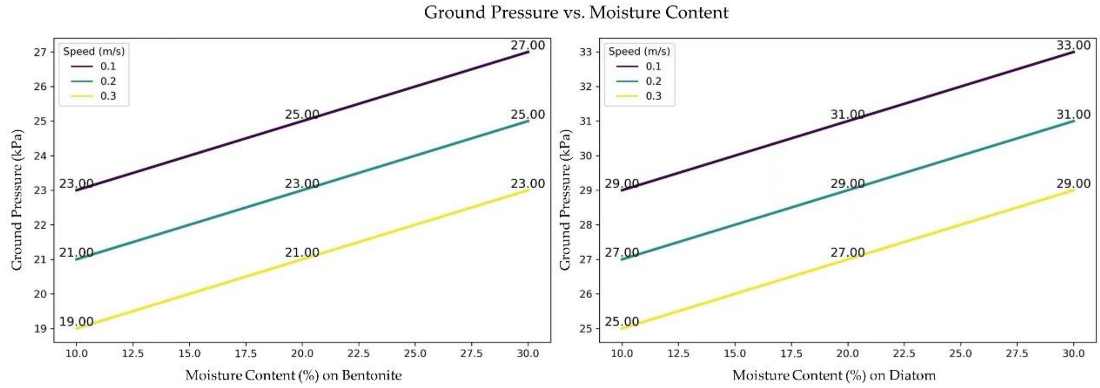

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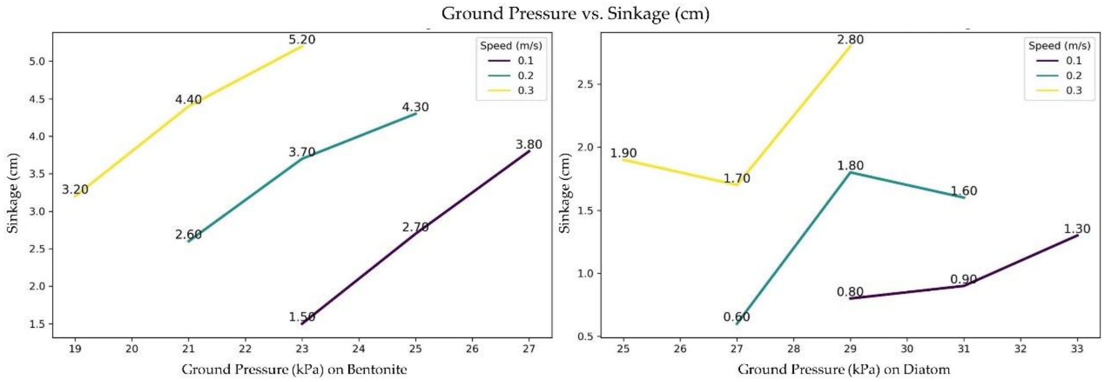

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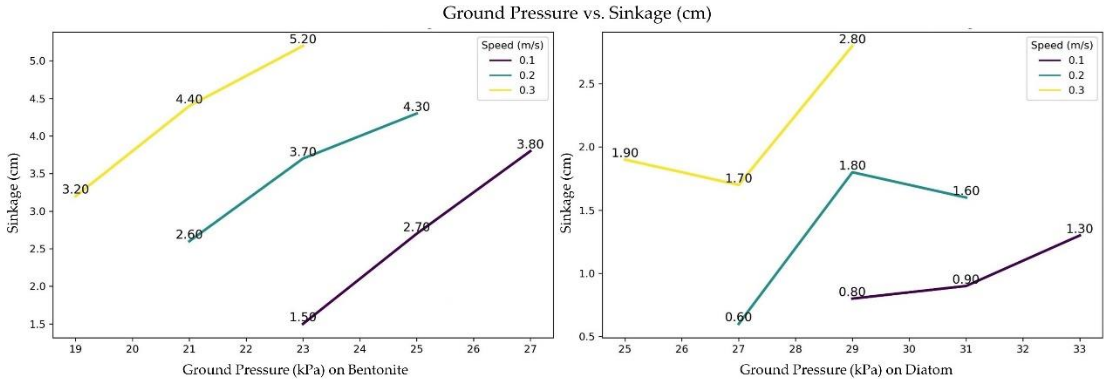

(c)

Figure 8. (a). The graph shows moisture (%) on the x-axis and ground pressure (kPa) on the y-axis**. (b).** The graph shows moisture (%) on the x-axis and sinkage (cm) on the y-axis. **(c).** The graph shows ground pressure (kPa) on the x-axis and sinkage (cm) on the y-axis.

Interestingly, when the speed is increased to 0.2 m/s, the ground pressure inversely correlates with moisture content, decreasing from 21 kPa to 25 kPa. This inverse correlation can signify a mechanical threshold for Bentonite, where increased kinetic energy (speed) may mitigate moisture's binding effect. However, the sinkage consistently rises, possibly indicating that while the ground may resist pressure effectively, it may not be as adept at supporting weight or volume at this speed. The trend is further accentuated at 0.3 m/s, where even lower ground pressures of 19 kPa to 23 kPa are contrasted with the highest sinkage values, suggesting diminished structural integrity of Bentonite at higher speeds and moisture levels, illustrated in Table 5.

Table 5. Rubber-Tracked Vehicle Sinkage, Ground Pressure, Speed Test Results.

Soil Type	Speed (m/s)	Moisture Content (±%)	Ground Pressure (kPa)	Sinkage (cm)
Bentonite	0.1	10	23	1.5

Bentonite	0.1	20	25	2.7
Bentonite	0.1	30	27	3.8
Bentonite	0.2	10	21	2.6
Bentonite	0.2	20	23	3.7
Bentonite	0.2	30	25	4.3
Bentonite	0.3	10	19	3.2
Bentonite	0.3	20	21	4.4
Bentonite	0.3	30	23	5.2
Diatom	0.1	10	29	0.8
Diatom	0.1	20	31	0.9
Diatom	0.1	30	33	1.3
Diatom	0.2	10	27	0.6
Diatom	0.2	20	29	1.8
Diatom	0.2	30	31	1.6
Diatom	0.3	10	25	1.9
Diatom	0.3	20	27	1.7
Diatom	0.3	30	29	2.8

In contrast, the behavior of diatom soil depicts a different picture. At the base speed of 0.1 m/s, even as ground pressures are notably higher than Bentonite (29 kPa to 33 kPa), sinkage values are comparatively subdued, ranging between 0.8 cm and 1.3 cm. Despite higher ground pressures, the relative stability in Diatom's sinkage alludes to its potentially higher shear strength or internal friction, possibly attributed to its structural composition. This hints at Diatom soil's inherent higher compaction or density, potentially due to its unique mineralogical composition [44]. As speeds increase to 0.2 m/s and 0.3 m/s, the ground pressures reduce across the moisture gradient, but there is a more erratic behavior in sinkage values. This erraticism could potentially underscore a complexity in 'Diatom's response to mechanical stress, revealing an intricate interplay between its physical structure and moisture content. This could indicate the intricate interplay between soil particle arrangement, moisture, and external pressure in Diatom soil, making it react differently than Bentonite.

3.4. Impact of moist soil content on sinkage exponent

Moisture content significantly affects soil mechanical properties, especially sinkage. Higher moisture content correlates with an increased sinkage exponent, indicating reduced load-bearing capacity as saturation levels rise. Elevated moisture content reduces effective stress, diminishing shear strength and increasing deformation. Assessing load-bearing capacity and sinkage propensity must account for soil moisture content. The moisture content, cohesive modulus, and sinkage exponent for Bentonite and Diatom soil types are displayed in Figure 9., and comprehensive data is shown in Table 6.

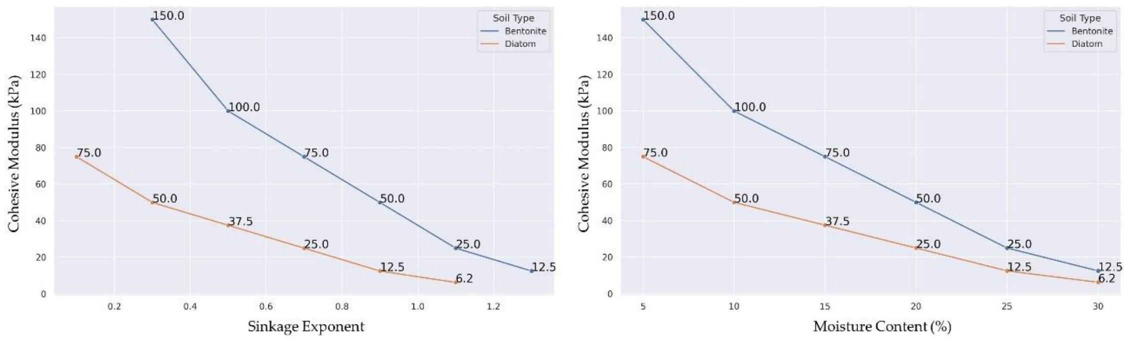

Figure 9. Bentonite and Diatom Sinkage exponent, Moisture, and Cohesive modulus.

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For Bentonite, there is an evident progressive increase in the sinkage exponent with increasing moisture content. Starting at 5% moisture, the sinkage exponent is recorded at 0.3 and ascends steadily, reaching 1.3 at a moisture content of 30%. This indicates a direct relationship between moisture levels and the sinkage behavior of Bentonite, suggesting that as the soil becomes wetter, its propensity to sink under pressure magnifies. Given these observations, it can be inferred that the complex interplay between water molecules and Bentonite soil particles may result in increased flexibility, thereby facilitating more significant sinkage under applied loads. Such behavior can have important implications, especially in construction or agricultural settings where precise knowledge of soil's response to moisture is paramount [45].

Contrarily, the cohesive modulus for Bentonite depicts an inverse relationship with moisture. Commencing at a robust 150 kPa at 5% moisture, this value dwindles consistently to 12.5 kPa at 30% moisture. This sharp decline underscores that as Bentonite becomes more saturated, its cohesive strength—or its ability to stick together—diminishes considerably. This weakening of cohesion with increased moisture content aligns with prior observations made in the field, emphasizing water's critical role in altering soil's mechanical properties. It is interesting to note that even a slight increase in moisture can lead to significant changes in the cohesive modulus, potentially highlighting the sensitivity of Bentonite to water content.

Table 6. Moisture Content, Cohesive Modulus, and Sinkage Exponent of Bentonite and Diatom.

Soil Type	Moisture Content (± %)	Sinkage Exponent	Cohesive modulus (kPa)
Bentonite	5	0.3	150
Bentonite	10	0.5	100
Bentonite	15	0.7	75
Bentonite	20	0.9	50
Bentonite	25	1.1	25
Bentonite	30	1.3	12.5
Diatom	5	0.1	75
Diatom	10	0.3	50
Diatom	15	0.5	37.5
Diatom	20	0.7	25
Diatom	25	0.9	12.5
Diatom	30	1.1	6.25

On the other hand, Diatom soil demonstrates a pattern somewhat parallel to Bentonite but with certain variations. The sinkage exponent for Diatom begins at a lower value of 0.1 for 5% moisture but experiences a consistent surge, reaching 1.1 at 30% moisture. This mirrors the trend observed in Bentonite, pointing to an increased sinkage susceptibility with moisture saturation. The cohesive modulus of Diatom, starting from 75 kPa at 5% moisture, follows a decreasing trajectory similar to that of Bentonite. However, by the time we reach a moisture content of 30%, the cohesive modulus descends to a mere 6.25 kPa, suggesting that Diatom, at higher moisture levels, may possess even lesser cohesive strength compared to Bentonite. The behavior examined in Diatom soil further establishes the pivotal role of moisture in dictating the structural characteristics of different soil types. Compared to Bentonite, the steeper decline in the cohesive modulus of Diatom might indicate the inherent differences in their compositions and how they interact with water.

The vehicle is equipped with high-precision pressure sensors strategically placed at contact points between the tracks and soil. A 6-channel FD0843 data acquisition system (illustrated in Supplementary Figure S7.), along with Computer-Enabled Ground Pressure Measurement Software (elucidated in Supplementary Figure S8.), records real-time pressure sinkage data at varying moisture levels and different sinkage in centimeters, as explained in Figure 10. A detailed analysis and interpretation is presented in Table 7. The results of the rubber-tracked vehicle testing revealed that the pressure sensor readings increased as soil moisture content and vehicle speed increased, as illustrated in Table 6. Compared to diatom soil, the results from the pressure sensor demonstrated

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that bentonite soil had consistently higher values. This is the explanation for the fact that bentonite soil contains a greater quantity of clay than diatom soil.

When compared to sand particles, clay particles have a higher porosity and smaller diameters than sand particles. It would imply that they can retain more water and produce a more closely linked soil than other soils. Because of the higher clay concentration in bentonite soil, vehicles have a more significant hurdle to penetrate, resulting in increased pressure sensor readings. Table 5 displays the recorded pressure sensor readings from the data logger during vehicle track testing. The experiment examined a soil bin composed of a mixture of Bentonite/Diatom soil and sand and gravel particles ranging from 2-5 mm. The moisture levels of the soil bed were set at 10%, 20%, and 30%, while the vehicle's speed was set at 0.1, 0.2, and 0.3 m/sec.

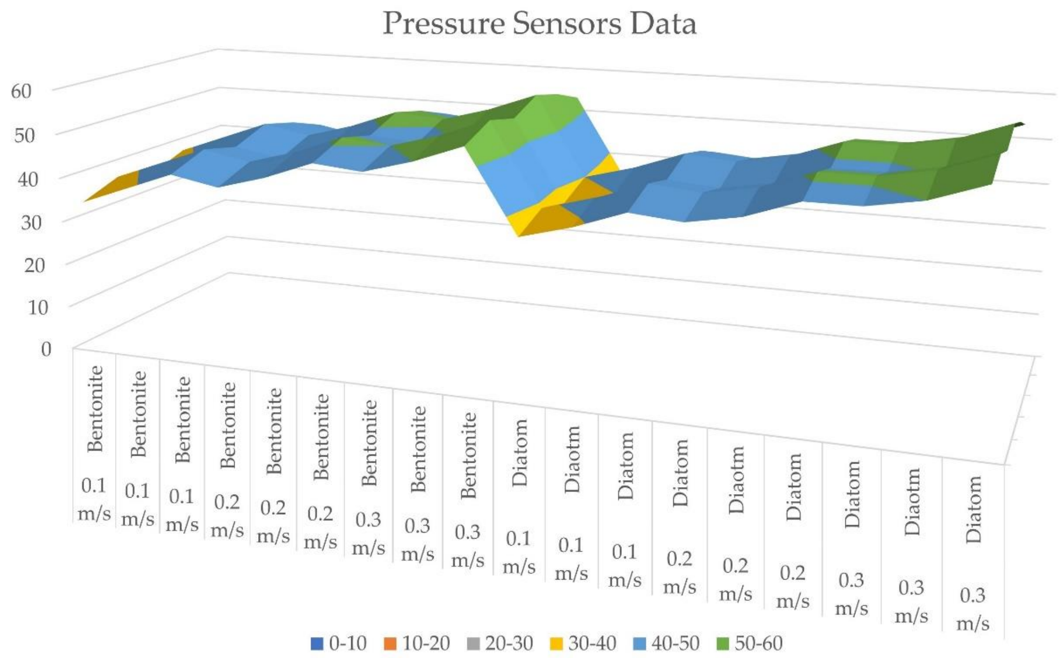

Figure 10. A graphical representation of Sensors Data collected from 6 pressure sensors at variable speeds (0.1, 0.2, and 0.3 m/sec).

Figure 10 depicts pressure changes measured by six sensors positioned in the soil bin at different moisture levels of Bentonite/Diatom (10%, 20%, and 30%) and various speeds of the rubber-tracked vehicle (0.1, 0.2, and 0.3 m/sec) as it traverses on the terrains. The corresponding graph presents tabulated data indicating the pressure measurements recorded by each sensor (Sensor 1 to Sensor 6) at varying speeds and moisture levels. Detailed data is shown in Table 6. This thorough presentation facilitates a meticulous examination regarding pressure distribution among sensors in response to changes in moisture content and vehicle speed. The plotted data provides vital information about the dynamic interactions between the rubber-tracked vehicle and the soil, allowing for a sophisticated comprehension of sinkage pressure patterns under specified experimental conditions.

The graph explains the complex correlation between pressure, moisture levels, and speed throughout all the sensors installed in the soil bin. The X-axis represents moisture levels ranging from 10% to 30%. Simultaneously, the y-axis represents pressure measurements in kilopascals (kPa). Each line on the graph represents a distinct speed category (0.1 m/sec, 0.2 m/sec, 0.3 m/sec), and the individual data points indicate the pressure measurements at specific moisture levels for each of the six sensors. The visual depiction directly compares pressure sinkage data for each sensor under various situations. The graphical illustration enhances comprehension of the intricate trends and patterns in the dataset, offering vital insights into the dynamics of pressure fluctuations concerning moisture levels and vehicle speeds.

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Table 7. Data Logging Table Showing Pressure Sensor Readings at 10%, 20%, and 30% Moisture Levels and Speed is Set to 0.1, 0.2, and 0.3m/sec.

Soil Type	Moisture Level (±%)	Speed (m/sec)	Sensor 1 (kPa)	Sensor 2 (kPa)	Sensor 3 (kPa)	Sensor 4 (kPa)	Sensor 5 (kPa)	Sensor 6 (kPa)
Bentonite	10	0.1	35	38	36	39	37	34
Bentonite	20	0.1	39	42	40	43	41	38
Bentonite	30	0.1	43	46	44	47	45	42
Diatom	10	0.1	36	39	37	40	38	35
Diatom	20	0.1	39	42	40	43	41	38
Diatom	30	0.1	43	46	44	47	45	42
Bentonite	10	0.2	41	44	42	45	43	40
Bentonite	20	0.2	44	47	45	48	46	43
Bentonite	30	0.2	48	51	49	52	50	47
Diatom	10	0.2	42	45	43	46	44	41
Diatom	20	0.2	44	47	45	48	46	43
Diatom	30	0.2	48	51	49	52	50	47
Bentonite	10	0.3	47	50	48	51	49	46
Bentonite	20	0.3	50	53	51	54	52	49
Bentonite	30	0.3	54	57	55	58	56	53
Diatom	10	0.3	48	51	49	52	50	47
Diatom	20	0.3	50	53	51	54	52	49
Diatom	30	0.3	54	57	55	58	56	53

The pace of the vehicle also significantly influenced the measurements of the pressure sensor. The pressure sensor data exhibited a positive correlation with the vehicle's speed. At higher speeds, the vehicle exerts tremendous stress on the terrain. A more potent force compacts the soil considerably, leading to elevated readings on the pressure sensor.

The study results show the potential implications for the development of off-road vehicles. The data gathered through laboratory-controlled experiments indicate that the soil type and moisture content can significantly impact the readings from the pressure sensor. This data can be used to design vehicles better adapted for various terrain types. The findings also suggest that the vehicle's speed can significantly impact the pressure sensor measurements. This information can be used to design vehicles that are optimally adapted for various operating velocities. Overall, the study, which encompasses track vehicle analysis, sinkage observations, soil behavior, ground pressure, and sinkage tests, enhanced our understanding of track vehicles' interaction with the soil. These insights have practical applications in off-road vehicle design, soil compaction assessment, and predicting soil behavior under varying loads.

4. Conclusions

To summaries, this study sheds light on the intricate relationship between tracked vehicles and various terrains, explicitly emphasizing the significant influence of soil moisture levels on the sinking of vehicles. It provided valuable insights into evaluating ground pressure, bearing capacity, and sinkage in rigid-flexible tracked vehicles operating on characterized terrain. Although the conventional terramechanical models, such as Bekker and Reece, have given us important insights, our research highlights the need for more advanced models that accurately represent the complex dynamics of soil-vehicle interactions in the actual world.

The noticeable variations in the sinking behavior found between Bentonite and Diatom soils, especially under different moisture levels, indicate the multifaceted nature of this phenomenon. By applying terramechanics principles and utilizing advanced sensor technologies such as CPT, moisture sensors, and data loggers, the study has contributed to a comprehensive understanding of the dynamic interaction between rubber-track vehicles and the soil substrate. Through the laboratory-controlled soil-bin test, the pressure sensors in the soil bin under the tracked vehicle gathered data at moisture levels of 10%, 20%, and 30%, and speeds of 0.1, 0.2, and 0.3 m/sec while traversing on Bentonite/Diatom. This dataset comprehensively investigates soil-vehicle interactions by examining how moisture levels and vehicle speed affect the pressure distribution in the soil bin under study. The investigation conducted in a controlled soil bin environment, utilizing a composite soil mixture of bentonite, diatom, and sand gravel under moist conditions, has allowed for the precise analysis of pressure-sinkage relationships and bearing capacity performance. These findings underline the necessity of accounting for soil type, moisture content, and their inherent physical qualities for building more exact terramechanical models. Incorporating these observations into future studies can drive progress in the design of off-road vehicles and enhance our understanding of terrain mechanics.

This knowledge is pivotal for optimizing vehicle performance and ensuring safe and efficient operation across diverse and challenging terrains. The methodologies explained in this study hold significant relevance for developing optimized vehicle-terrain systems, offering potential applications in off-road vehicle design, agricultural machinery, and military operations on varied terrains. Ultimately, the research highlights the relevance of employing a scientific methodology to enhance our comprehension of the behavior of rubber-tracked vehicles in particular terrains, contributing to the evolution of soil mechanics and off-road vehicle engineering. It lays a solid foundation for further exploration and innovation in the field of terramechanics. It provides a basis for enhancing the efficiency, safety, and sustainability of tracked vehicle operations in diverse operational environments.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org. Attached is all the technical information about the sensor, detailed experimental setup, and data acquisition.

Author Contributions: Conceptualization, OR and YN; methodology, OR and YN; software, OR; validation, OR and MHX; formal analysis, OR and YN; investigation, OR and YN; resources, OR; data curation, OR; writing—original draft preparation, OR; writing—review and editing, OR and YN; visualization, YN; supervision, YN; project administration, YN, MHX; funding acquisition, YN. All authors have read and agreed to the published version of the manuscript.

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References

1. Wong, J.Y. Terramechanics and Off-Road Vehicle Engineering: Terrain Behaviour. *off-road vehicle performance and design* **2010**, 129–149.

2. Zhang, Y.; Qiu, M.; Liu, X.; Li, J.; Song, H.; Zhai, Y.; Hu, H. Research on Characteristics of Tracked Vehicle Steering on Slope. *Math Probl Eng* **2021**, *2021*, 1–18.
3. Li, J.; Khajepour, A.; Huang, Y.; Wang, H.; Tang, C.; Qin, Y. A New Coordinated Control Strategy for Tracked Vehicle Ride Comfort. *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics* **2018**, *232*, 330–341.
4. Wong, J.Y. Optimization of the Tractive Performance of Articulated Tracked Vehicles Using an Advanced Computer Simulation Model. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* **1992**, *206*, 29–45.
5. Beketov, S.A. The Concept of the Controlled Movement of the Tracked Vehicle. *Izvestiya MGTU MAMI* **2018**, *12*, 16–20.
6. Reece; Wong, J.-Y., A.R. Prediction of Rigid Wheel Performance Based on the Analysis of Soil-Wheel Stresses Part I. Performance of Driven Rigid Wheels. *J Terramech* **1967**, *4*, 81–98.
7. Wong, J.-Y.; Reece, A.R. Prediction of Rigid Wheel Performance Based on the Analysis of Soil-Wheel Stresses: Part II. Performance of Towed Rigid Wheels. *J Terramech* **1967**, *4*, 7–25.
8. Bekker, M.G. Introduction to Terrain-Vehicle Systems. Part i: The Terrain. Part Ii: The Vehicle. **1969**.
9. Shibly, H.; Iagnemma, K.; Dubowsky, S. An Equivalent Soil Mechanics Formulation for Rigid Wheels in Deformable Terrain, with Application to Planetary Exploration Rovers. *J Terramech* **2005**, *42*, 1–13.
10. Ruslan, N.A.I.; Amer, N.H.; Hudha, K.; Kadir, Z.A.; Ishak, S.A.F.M.; Dardin, S.M.F.S. Modelling and Control Strategies in Path Tracking Control for Autonomous Tracked Vehicles: A Review of State of the Art and Challenges. *J Terramech* **2023**, *105*, 67–79.
11. Wong, J.Y. Dynamics of Tracked Vehicles. *Vehicle system dynamics* **1997**, *28*, 197–219.
12. Shafaei, S.M.; Mousazadeh, H. On the Power Characteristics of an Unmanned Tracked Vehicle for Autonomous Transportation of Agricultural Payloads. *J Terramech* **2023**, *109*, 21–36.
13. Dallas, J.; Jain, K.; Dong, Z.; Sapronov, L.; Cole, M.P.; Jayakumar, P.; Ersal, T. Online Terrain Estimation for Autonomous Vehicles on Deformable Terrains. *J Terramech* **2020**, *91*, 11–22.
14. Nampoothiri, M.G.H.; Vinayakumar, B.; Sunny, Y.; Antony, R. Recent Developments in Terrain Identification, Classification, Parameter Estimation for the Navigation of Autonomous Robots. *SN Appl Sci* **2021**, *3*, 1–14.
15. Bekker, M.G. Introduction to Terrain-Vehicle Systems. Part i: The Terrain. Part Ii: The Vehicle. **1969**.
16. Wong, J.Y. *Theory of Ground Vehicles*; John Wiley & Sons, 2022; ISBN 1119719704.
17. Harnisch, C.; Lach, B.; Jakobs, R.; Troulis, M.; Nehls, O. A New Tyre–Soil Interaction Model for Vehicle Simulation on Deformable Ground. *Vehicle system dynamics* **2005**, *43*, 384–394.
18. Wong, J.Y. *Theory of Ground Vehicles*; John Wiley & Sons, 2022; ISBN 1119719704.
19. Gotteland, P.; Benoit, O. Sinkage Tests for Mobility Study, Modelling and Experimental Validation. *J Terramech* **2006**, *43*, 451–467.
20. Mohtashami, S.; Eliasson, L.; Jansson, G.; Sonesson, J. Influence of Soil Type, Cartographic Depth-to-Water, Road Reinforcement and Traffic Intensity on Rut Formation in Logging Operations: A Survey Study in Sweden. *Silva Fennica* **2017**, *51*.
21. Liu, K.; Ayers, P.; Howard, H.; Anderson, A. Influence of Soil and Vehicle Parameters on Soil Rut Formation. *J Terramech* **2010**, *47*, 143–150.
22. Diserens, E.; Défossez, P.; Duboisset, A.; Alaoui, A. Prediction of the Contact Area of Agricultural Traction Tyres on Firm Soil. *Biosyst Eng* **2011**, *110*, 73–82.
23. Meirion-Griffith, G.; Spenko, M. A Modified Pressure–Sinkage Model for Small, Rigid Wheels on Deformable Terrains. *J Terramech* **2011**, *48*, 149–155.
24. Solis, J.M.; Longoria, R.G. Modeling Track–Terrain Interaction for Transient Robotic Vehicle Maneuvers. *J Terramech* **2008**, *45*, 65–78.
25. Szpaczyńska, D.; Łopatka, M.J.; Krogul, P. Susceptibility Modeling of a Rubber Track for Lightweight Mobile Robots. *Applied Sciences* **2023**, *13*, 10533.
26. Hu, K.; Cheng, K. Dynamic Modelling and Stability Analysis of the Articulated Tracked Vehicle Considering Transient Track-Terrain Interaction. *Journal of Mechanical Science and Technology* **2021**, *35*, 1343–1356.
27. Shibly, H.; Iagnemma, K.; Dubowsky, S. An Equivalent Soil Mechanics Formulation for Rigid Wheels in Deformable Terrain, with Application to Planetary Exploration Rovers. *J Terramech* **2005**, *42*, 1–13.
28. Ani, O.A.; Uzoejinwa, B.B.; Ezeama, A.O.; Onwualu, A.P.; Ugwu, S.N.; Ohagwu, C.J. Overview of Soil-Machine Interaction Studies in Soil Bins. *Soil Tillage Res* **2018**, *175*, 13–27.
29. Badgujar, C.M.; Flippo, D.; Brokesh, E.; Welch, S. Experimental Investigation on Traction, Mobility, and Energy Usage of a Tracked Autonomous Ground Vehicle on a Sloped Soil Bin. *Journal of the ASABE* **2022**, *65*, 835–847.
30. Badgujar, C.; Flippo, D.; Welch, S. Artificial Neural Network to Predict Traction Performance of Autonomous Ground Vehicle on a Sloped Soil Bin and Uncertainty Analysis. *Comput Electron Agric* **2022**, *196*, 106867.

31. Ivanov, S.É.; Belyakov, A. V Diatomite and Its Applications. *Glass & Ceramics* **2008**, *65*.
32. Diaz-Rodríguez, J.A. Diatomaceous Soils: Monotonic Behavior. In *Deformation characteristics of geomaterials*; IOS Press, 2011; pp. 865–871.
33. Wagner, J.-F. Mechanical Properties of Clays and Clay Minerals. In *Developments in clay science*; Elsevier, 2013; Vol. 5, pp. 347–381 ISBN 1572-4352.
34. Chaudhary, V.; Yadav, J.S.; Dutta, R.K. Geotechnical Properties of Bentonite Mixed with Nanosilica. *Multiscale and Multidisciplinary Modeling, Experiments and Design* **2023**, 1–18.
35. Tang, A.-M.; Cui, Y.-J.; Eslami, J.; Défossez, P. Analysing the Form of the Confined Uniaxial Compression Curve of Various Soils. *Geoderma* **2009**, *148*, 282–290.
36. Kochmanov, N.; Tanakai, H. Influence of the Soil Fabric on the Mechanical Properties of Unsaturated Clays. *Soils and Foundations* **2011**, *51*, 275–286.
37. Cuisinier, O.; Auriol, J.-C.; Le Borgne, T.; Deneele, D. Microstructure and Hydraulic Conductivity of a Compacted Lime-Treated Soil. *Eng Geol* **2011**, *123*, 187–193.
38. Wang, Q.; Cui, Y.-J.; Tang, A.M.; Barnichon, J.-D.; Saba, S.; Ye, W.-M. Hydraulic Conductivity and Microstructure Changes of Compacted Bentonite/Sand Mixture during Hydration. *Eng Geol* **2013**, *164*, 67–76.
39. Alaoui, A.; Helbling, A. Evaluation of Soil Compaction Using Hydrodynamic Water Content Variation: Comparison between Compacted and Non-Compacted Soil. *Geoderma* **2006**, *134*, 97–108.
40. Zhang, S.; Grip, H.; Lövdahl, L. Effect of Soil Compaction on Hydraulic Properties of Two Loess Soils in China. *Soil Tillage Res* **2006**, *90*, 117–125.
41. Samuel, T.M.; Ajav, E.A. Optimum Tillage System for Pepper Production in an Alfisol of South-Western Nigeria. *Afr J Agric Res* **2010**, *5*, 2647–2652.
42. Botta, G.F.; Becerra, A.T.; Tourn, F.B. Effect of the Number of Tractor Passes on Soil Rut Depth and Compaction in Two Tillage Regimes. *Soil Tillage Res* **2009**, *103*, 381–386.
43. Mishra, A.K.; Ohtsubo, M.; Li, L.Y.; Higashi, T. Influence of the Bentonite on the Consolidation Behaviour of Soil–Bentonite Mixtures. *Carbonates Evaporites* **2010**, *25*, 43–49.
44. Sha, F.; Xi, M.; Chen, X.; Liu, X.; Niu, H.; Zuo, Y. A Recent Review on Multi-Physics Coupling between Deep-Sea Mining Equipment and Marine Sediment. *Ocean Engineering* **2023**, *276*, 114229.
45. Yang, C.; Yang, G.; Liu, Z.; Chen, H.; Zhao, Y. A Method for Deducing Pressure–Sinkage of Tracked Vehicle in Rough Terrain Considering Moisture and Sinkage Speed. *J Terramech* **2018**, *79*, 99–113.