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Evaluating the Effect of Soil Deformation Rate on the Estimation of the Energy Consumption in Soil-Tire Interactions Using the Pressure-Sinkage Equation

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Abstract

Understanding soil deformation dynamics is critical in various fields, such as off-road vehicle mobility, agriculture, and soil mechanics. In particular, evaluating soil-tire interactions is essential for optimizing energy consumption and minimizing the negative effects of soil compaction. This study investigates the effect of soil deformation rates on the pressure-sinkage relationship and energy consumption using a controlled soil bin environment and a bevameter system. The primary objective of the study is to examine how different traffic levels and varying penetration rates influence the energy required to achieve specific sinkage depths. The study employed a completely randomized block design, with each treatment replicated three times to ensure precision and reliability. Quantitative measurements were obtained using a load cell attached to a bevameter, capturing the forces at a sampling frequency of 30 Hz. Results demonstrated a significant influence of both traffic level and penetration velocity on soil resistance and energy consumption. For the larger plate, the pressure required for penetration increased with higher velocities and traffic levels. At the highest velocity (45 mm s^{-1}) and with 8 passes, the pressure needed for sinkage was maximal. The energy consumption for each scenario was calculated by integrating the area under the force-sinkage curve. The analysis of variance (ANOVA) revealed that the number of wheel passes, plate size, and penetration velocity significantly affected energy consumption. At the highest sinkage depth (60 mm), the energy consumption for the larger plate at 45 mm s^{-1} and with 8 passes was nearly double that of the smaller plate. These results emphasize the importance of considering both traffic-induced compaction and velocity when designing off-road vehicles or agricultural machinery that interact with deformable terrains.

Keywords: Bevameter, Penetration rate, Soil deformation, Terramechanics, Multiple passes

Introduction

The understanding of soil deformation holds paramount importance in various fields, such as soil mechanics, traction theory, soil compaction, and sustainable agriculture practices. The dynamics of soil deformation are inherently complex, particularly when considering the interaction between off-road vehicles and soil, which typically exhibits dynamic behavior (Golanbari & Mardani, 2024; Majdoubi, Masmoudi, & Elharif, 2024). The quality of soil deformation is influenced by factors such as load parameters, device

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geometry, and the dynamic characteristics of soil interaction (Golanbari & Mardani, 2023; Taheri & Tatsuoka, 2015). Moreover, an in-depth study of soil deformation dynamics is indispensable for practitioners, such as agricultural workers and off-road vehicle operators, who encounter diverse and often unfamiliar terrain conditions during their operations (Gonzalez & Iagnemma, 2018). The main advantage with a bevameter is that it is designed to measure several parameters with the same equipment (Mardani & Golanbari, 2024). Earl and Alexandrou (2001) used a tractor-mounted bevameter for outdoor measurement of soil pressure-sinkage parameters using three different shapes of pressure plates.

The study conducted by Taghavifar and Mardani (2014) investigated the influence of tire characteristics on energy consumption management in terramechanics. They utilized a soil bin facility under controlled conditions and examined the effects of tire vertical load, velocity, and tire inflation pressure on energy consumption. In contrast with earlier literature reports, their findings revealed discrepancies regarding the impact of tire parameters on wasted energy and rolling resistance.

The complex influence of diverse factors on pressure-sinkage relationship, particularly across varied penetration rates and probe sizes, was explored in the study conducted by Apfelbeck, Kuß, Rebele, and Schäfer (2011). The importance of these variables in determining the optimal testing conditions necessary to validate soil contact models for specific wheel types under defined operational parameters was highlighted in their study.

Schematic diagrams are utilized to illustrate the dynamic forces involved in off-road wheel mechanics, facilitating a comprehensive understanding of the phenomenon. Fig. 1 depicts the gross traction (GT), which can be calculated as the summation of the net traction (NT) and the rolling resistance (RR) forces (ASAE Standard S296.5, 2018).

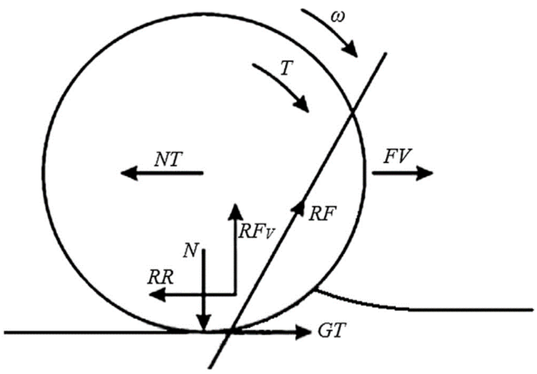

Fig. 1. Illustration of the fundamental forces and velocities acting upon a wheel, encompassing the resultant soil reaction force

It is notable that, to set the wheels in motion, the torque generated by the engine is used to create traction so that the rolling resistance is neutralized. Additionally, Bekker established the basis for quantifying rolling resistance from a mechanical soil strength perspective. He proposed that at the tire-soil contact area, the wheel acts like a continuously penetrating plate to a depth equal to the rut depth formed by the wheel's load. Equations 1 and 2 were introduced to calculate the average pressure applied to the soil from a plate pressed into the soil as a function of sinkage depth (Z), and the energy loss of the process, respectively, as outlined by Bekker (1969).

$$P_{ave} = \left(\frac{k_c}{b} + k_\varphi\right).Z^n \qquad (1)$$

$$W_o = l\frac{(k_c + bk_\varphi)}{n+1}\left[\frac{F}{l(k_c + bk_\varphi)}\right]^{\frac{n+1}{n}} \qquad (2)$$

Eq. 2 is used to theoretically calculate the work required for penetrating a plate into soil, where W_0 represents the work done by the load of F (kN) acting on the plate at the maximum sinkage depth of Z_0. Furthermore, this equation encompasses pivotal factors such as soil sinkage coefficients (k_c and k_ϕ), plate width (b) and length (l), and a sinkage exponent (n) derived from sinkage tests.

However, this oversimplified explanation only scratches the surface of the complex phenomenon known as rolling resistance. Recent research has delved deeper into understanding the factors influencing rolling resistance, particularly focusing on tire characteristics. In a notable experiment conducted by Taghavifar and Mardani (2013), the relationship between tire characteristics and rolling resistance was thoroughly investigated. Their study emphasized the crucial role of the contact area in determining rolling resistance, proposing it as a practical metric for quantifying this phenomenon.

The primary objective of this study is to evaluate the effects of varying soil deformation rates on pressure distribution and energy consumption during interactions with different plate sizes in a controlled environment. Specifically, this research aims to assess how different traffic levels (no pass, 4 passes, and 8 passes) and varying penetration velocities (15 mm s^{-1}, 30 mm s^{-1}, and 45 mm s^{-1}) affect soil compaction and resistance at different sinkage depths. By analyzing the energy consumption patterns and pressure-sinkage relationships, this study seeks to provide deeper insights into the mechanical behavior of soils under repeated loads. The findings aim to enhance models of soil-structure interactions for applications in off-road mobility and agricultural machinery.

Materials and Methods

For the measurement of soil parameters, a 200 kg capacity S-shaped load cell was accurately calibrated and positioned vertically between the sinkage plate and the bevameter shaft. This load cell served as a critical component for accurately quantifying soil resistance. The data obtained from the load cell were transmitted to a data acquisition system, which comprised a data logger, digital indicators, and a laptop. The data transmission occurred at a sampling frequency of 30 Hz, ensuring high-resolution data capture throughout the experiment process.

Fig. 2 provides a visual representation of the system, illustrating the arrangement of the equipment within the soil bin facility.

Fig. 2. Overall configuration of the soil bin

Fig. 3. Tools used for soil preparation: ploughing (top left), rake (top right), leveling board (bottom left), and rolling (bottom right)

Soil preparation

Before conducting the experiments, soil preparation was carried out using loosening and leveling tools (Fig. 3). Table 1 shows some properties of the soil used for the bevameter tests.

In this study, two plates were used to determine the pressure-sinkage relationship. Also, the independent variables of penetration rate and the number of passes, according to Table 1, were considered in performing the experiments.

The soil bin was filled with clay-loam soil to ensure precise experimental outcomes. Various tools, including a harrow, leveler, and roller, were used to meticulously prepare the soil bed within the soil channel, thereby guaranteeing the reliability and accuracy of the experimental results.

Fig. 4 and Fig. 5 illustrate the complete soil bin-mounted bevameter unit, along with the details of its design and construction.

Penetration velocity tests

This study investigates the influence of penetration velocity and tool geometry on soil parameters within bevameter test configurations, alongside the estimation of wasted energy under varying traffic passes. Two distinct rectangular plates are employed for each penetration velocity. Testing procedures contain three penetration velocities, spanning from the maximum attainable velocity of the bevameter to the lower velocities typical of agricultural implements. Each test includes three replications to ensure precision and reliability.

Table 1- Experimental soil texture and properties

Parameter	Value
Sand	35%
Silt	22%
Clay	43%
Moisture content (dry base)	8%
Bulk density	1460 kg cm^{-3}
Young's modulus	0.3 MPa
Poisson's ratio	0.29
Angle of internal friction	32

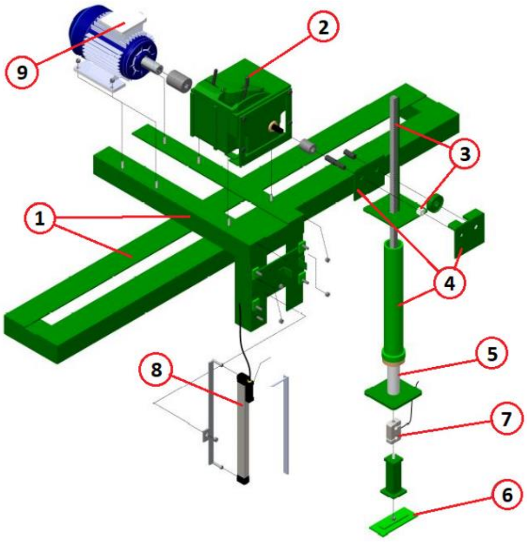

Fig. 4. Construction of the bevameter unit for soil characterization: 1. Chassis, 2. Gearbox, 3. Rail, 4. Support and Guide, 5. Shaft, 6. Bekker Plate, 7. Load cell, 8. Linear Encoder, and 9. 5.5 kW electromotor

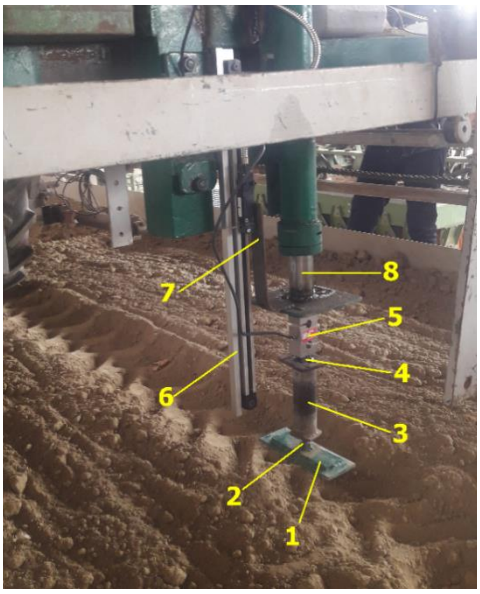

Fig. 5. A photograph of the bevameter mounted on the soil bin chassis: 1. Bekker Plate, 2. Screw, 3. Connection Rod 4. Screw, 5. Load cell, 6. MLC320 Linear Encoder, 7. Connector, and 8. Shaft

To ensure precise collection of rolling resistance data, a soil bin facility was utilized rather than conducting field experiments. This experimental setup provided a controlled environment and allowed for the inclusion of essential equipment such as a wheel carriage, single-wheel tester, bevameter, and various tillage tools along the track. The wheel carriage was propelled by a three-phase, 22 kW electromotor, which was powered by a chain system. Additionally, an inverter was employed to facilitate speed adjustments during testing procedures.

The bevameter system is a comprehensive setup designed to measure and analyze soil behavior under vehicle loads. It consists of various components that work together to ensure accurate and reliable testing results. The chassis and main frame, mounted on the soil bin carrier, provide structural support and stability against mechanical loads. They are constructed using L-shape and rectangular profiles, ensuring the system's integrity during testing. The power unit of the bevameter applies a vertical load to penetrate the pressure plates into the soil at different sinkage velocities. It includes a three-phase 5 kW electromotor connected to a mechanical jack. The motor's revolution control is achieved through a gearbox and an inverter, allowing for the adjustment of penetration velocity levels. To measure the applied vertical load, an S-type load cell (DBBP, Bongshin, South Korea), with a capacity of 10 kN was used. The load cell can be customized to accommodate various load requirements, providing precise measurements during testing. Additionally, a linear position transducer (MLC320, Atek, Türkiye), with a displacement of 400 mm and a resistance of 4 kΩ is used to measure the vertical displacement or sinkage of the pressure plates. This enables accurate assessment of the plates' penetration depth into the soil. The data acquisition system plays a crucial role in collecting and storing force and displacement data. It incorporates an interface that powers the transducers and processes the output signals in real-time. This interface (Azma120, Abzar Azma, Iran) also facilitates the storage of data in up to 10 different channels as an Excel file on external memory, enhancing data management and analysis capabilities.

The vertical motion of the shaft initiates the displacement of the bevameter probe into the soil. Consequently, load cells are activated, transmitting signals to the data acquisition system. The bevameter test is widely used in soil mechanics to measure the mechanical properties of soil under loading, such as its bearing capacity, pressure-sinkage relationships, and shear strength. This test typically involves pressing a circular or rectangular plate into the soil to evaluate how the soil reacts under varying loads. In performing Bekker bevameter tests, two different plate sizes are used to understand the soil's response at varying surface contact areas (Fig. 6). The test involves applying vertical pressure to the soil through these plates while monitoring the sinkage, which is the depth of penetration into the soil. The primary reason for using two plate sizes in the bevameter test is to evaluate the pressure-sinkage exponent, represented as n in Eq. 1, a key parameter in Bekker's pressure-sinkage model. This exponent helps determine the nonlinear relationship between the applied load and the resulting deformation in the soil. Moreover, by comparing the results of the two plate sizes, the cohesion modulus (k_c) and friction modulus (k_φ) of the soil can be estimated (Eq. 1).

Calculation of Soil Parameters Using the Bekker's Method

Following the collection of pressure-sinkage data, Bekker's equations can be expressed separately for each plate, as shown in equations 3 and 4.

$$P_1 = \left(\frac{k_c}{b_1} + k_\varphi\right).Z_1{}^n \tag{3}$$

$$P_2 = \left(\frac{k_c}{b_2} + k_\varphi\right).Z_2{}^n \tag{4}$$

To solve Bekker's equations, the logarithms of these equations can be written as linear equations 5 and 6.

$$logP_1 = nlog(Z_1) + log\left(\frac{k_c}{b_1} + k_\varphi\right) \tag{5}$$

$$logP_2 = nlog(Z_2) + log\left(\frac{k_c}{b_2} + k_\varphi\right) \tag{6}$$

First, by using one of each plate at two different penetration depths, two pressures are obtained. Then by writing two Becker equation relations for these two states and calculating the ratio of the two sides of the relations, n is directly obtained as the slope of the line with a similar amount for both plates.

In the next step, by using two Becker equations obtained from two plates with different widths and considering a certain amount of sinkage for each of them (Z_1 and Z_2) and the resulting pressures (P_1 and P_2), a two-equation system with two unknowns in terms of k_c and k_φ will be obtained as:

$$k_c = \frac{(P_1 - P_2)b_1 b_2}{(b_2 - b_1)Z_2{}^n} \tag{7}$$

$$k_{\varphi} = \frac{P_1}{Z_1^n} - \frac{k_c}{b_1} \tag{8}$$

These parameters are essential for understanding the soil bearing capacity and behavior under different loading scenarios.

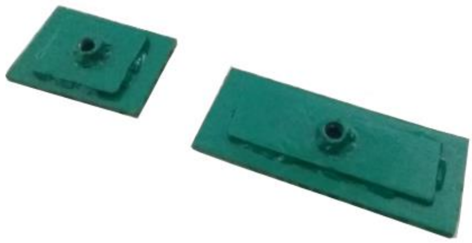

Fig. 6. Sinkage plates with two different sizes (70 × 105 mm and 70 × 175 mm)

Pressure–sinkage tests

The methods for determining soil parameters outlined in the preceding section offer a means to characterize the soil under analysis with dependable values based on the selected pressure-sinkage relationship. Prior to commencing measurement operations aimed at identifying the influence of the test setup on soil parameters, it is imperative to ascertain an appropriate soil preparation method. This ensures the attainment of reproducible and reliable measurement outcomes.

The experiment investigated the impact of different vertical bevameter probe rates (15, 30, and 45 mm s^{-1}), in conjunction with the number of wheel passages (0, 4, and 8), utilizing two sizes of sinkage plates.

Table 2 presents the details of the experimental treatments. The experiments were carried out in a completely randomized block design, with each treatment replicated three times.

Table 2- Summary of experimental parameters

Independent parameters		
Wheel passage	**probe velocity (mms^{-1})**	**Sinkage plates (mm)**
0	15	70×105, 70×175
4	30	70×105, 70×175
8	45	70×105, 70×175

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The analysis of variance (ANOVA) was done on the experimental data using Minitab software. Variables were included in the model if they exhibited statistical significance at the 0.01 level. The investigated variables were traffic, probe velocity, and their interaction.

Results and Discussion

Analysis of Variance

The Analysis of Variance (ANOVA) is a statistical method used to analyze the differences among group means and their associated variances. It helps in determining whether there are any statistically significant differences between the means of categorical independent variables affecting a dependent variable. In experimental studies, ANOVA is commonly used to assess the influence of different factors and their interactions on the observed outcomes. It is particularly effective when dealing with multiple factors and levels, as in this study, where multiple variables like plate size, number of passes, sinkage, and penetration rate are evaluated for their effect on energy consumption in soil deformation tests.

In the provided ANOVA table (Table 3), the primary factors affecting the energy consumption and pressure response during soil deformation tests are sinkage, plate size, and number of passes. Among these, sinkage has the most significant impact, as evidenced by its extremely high F-value (4980.76) and a p-value of less than 0.0001. This indicates that changes in the sinkage depth greatly influence the pressure-sinkage relationship and energy requirements. Similarly, plate size and number of passes also show significant effects, with F-values of 1439.35 and 1391.50, respectively, both with p-values less than 0.0001. These findings suggest that larger plate sizes and increased numbers of passes over the soil contribute substantially to increased soil compaction and energy consumption.

Table 3- Analysis of variance of the effect of parameters on energy consumption

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Plate size (mm)	1	33419	33419	1436.17	0.000
Number of passes	2	64616	32308	1388.43	0.000
Sinkage (mm)	3	346934	115645	4969.76	0.000
Penetration rate (mm s^{-1})	2	5301	2650	113.90	0.000
Plate size (mm)×Number of passes	2	5900	2950	126.76	0.000
Plate size (mm)×Sinkage (mm)	3	20356	6785	291.60	0.000
Plate size (mm)×Penetration rate (mm s^{-1})	2	123	62	2.65	0.074
Number of passes×Sinkage (mm)	6	37116	6186	265.84	0.000
Number of passes×Penetration rate (mm s^{-1})	4	1564	391	16.80	0.000
Sinkage (mm)×Penetration rate (mm s^{-1})	6	2866	478	20.53	0.000
Error	184	4282	23		
Total	215	522478			

Furthermore, several interaction effects are also significant. For instance, the interaction between plate size and number of passes ($F = 127.05$, $p < 0.0001$) indicates that the combined effect of these two factors significantly alters the energy consumption. The number of passes and sinkage interaction is also highly significant ($F = 266.43$, $p < 0.0001$), suggesting that the effect of the number of passes becomes more pronounced with increased sinkage depths. Overall, the ANOVA results highlight that these factors and their interactions must be carefully considered to optimize energy consumption and soil resistance in practical applications, such as off-road mobility or agricultural operations.

During the initial stage of plate sinkage, there is observable soil compaction, as illustrated in Figures 7 to 10. In the pressure-sinkage curves, within the range of 0 to 15 mm, compaction remains consistent, showing no significant variation across different penetration rates or pass levels. At this stage, soil compaction occurs directly beneath the plates, and the curve characteristics remain unaffected by the plate dimensions. As sinkage increases, as shown in Fig. 7, particularly between depths of 25 to 60 mm, the pressure-sinkage curves exhibit a consistent and smooth slope. At this point, the rectangular fracture area beneath the loading plate’s transitions from a rectangular shape into an incomplete or full cone-shaped form. This transformation occurs due to the initiation of lateral compression and soil flow, which marks the shift of the failure zone into a conical shape.

Fig. 7 illustrates the effect of varying penetration rates (15 mm s^{-1}, 30 mm s^{-1}, and 45 mm s^{-1}) and passage levels (no pass, 4 passes, and 8 passes) on the pressure required to achieve specific sinkage depths. Fig. 7A, with a smaller plate (70 × 105 mm), illustrates a clear trend where the pressure required for penetration increases with higher velocities and passage levels. The graphs obtained from a penetration rate of 15 mm s^{-1} at all pass levels show the minimum pressure required to increase penetration. However, by increasing the number of passes to 4 and 8, the pressure increases at a higher penetration rate for the same level of sinkage.

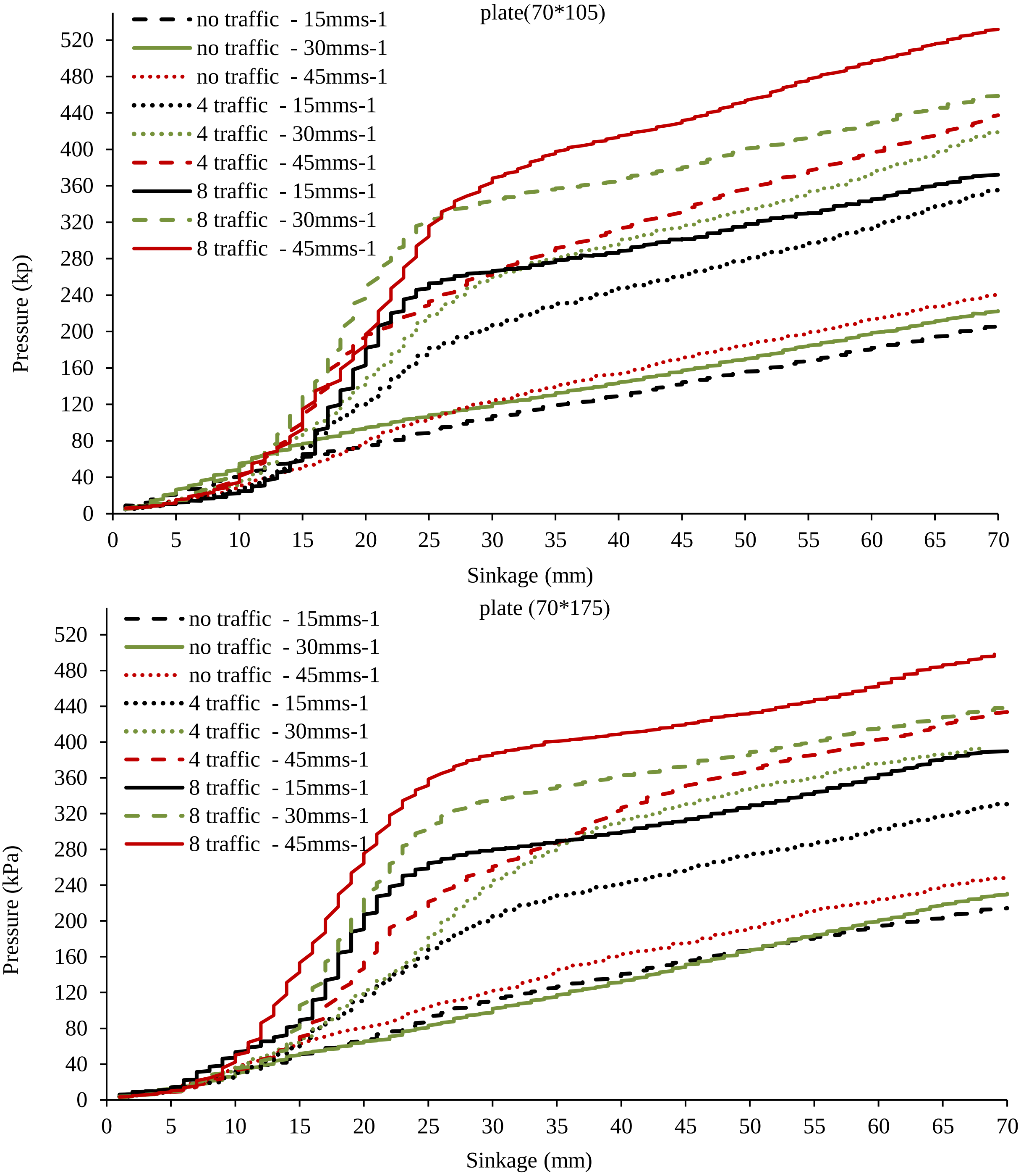

Fig. 7. Pressure-sinkage curves for two different rectangular plates: (A) 70 × 105 mm, and (B) 70 × 175 mm

This change signifies a modification in the soil's initial condition and an enhancement of soil compaction due to repeated loading. The 45 mm/s velocity plots exhibit the highest pressures at all penetration levels, indicating that higher penetration rates require more pressure for a given amount of soil deformation than lower penetration rates.

Fig. 7B shows the resulting soil pressure-settlement curves from the larger plate (70 x

175 mm). The overall trend is similar, but the pressure required for the same amount of sinkage is significantly lower than the smaller plate. This occurs while the force applied to reach a certain sinkage is much higher for the larger plate than for the smaller plate. The stabilization of the sinkage occurs more quickly with a larger plate, suggesting that an increased contact area reduces deformation, even under high-pressure conditions. The pressure difference required for plate penetration between 4 and 8 passes becomes more pronounced when using the larger plate, highlighting the increased compaction pressure with a larger surface contact area. In both graphs, as the penetration rate increases, the pressure required to achieve similar levels of soil sinkage rises across all pass conditions, with the 45 mm s^{-1} penetration rate exhibiting the highest resistance. These findings indicate that larger plate sizes and higher speeds exacerbate traffic-induced soil compaction, making soil deformation under pressure progressively more difficult.

The results of the pressure-sinkage data from the experiments showed a similar trend aligned with research in this field (Brunskill *et al.*, 2011; Golanbari, Mardani, Hosainpour, & Taghavifar, 2023; Kruger, Els, & Hamersma, 2023). This shows that the designed bevameter has significant capability for data acquisition.

To estimate Bekker coefficients (k_c, k_φ, and n), at least two penetration experiments using different lengths of plates are required (Bekker, 1960).

The average soil parameters for three replicates were determined using Bekker's equations presented in Table 4.

As indicated in Table 4, the values of n have an increasing trend with increasing traffic and penetration velocity, and the reason for this is the increase in the slope of the pressure-sinkage curves with the increase of the above two independent parameters.

Table 4- Identified Bekker parameters for different wheel passes and penetration velocities

Pass	**0**			**4**			**8**		
Penetration rate (mm s^{-1})	15	30	45	15	30	45	15	30	45
n	0.973	0.976	1.08	1.243	1.287	1.319	1.223	1.278	1.425
k_ϕ (kN (m^{n+1})$^{-1}$)	620	665	778	808	757	666	913	745	772
k_c (kN (m^{n+2})$^{-1}$)	264.34	211.84	29.40	-47.15	21.77	135.98	153.04	72.45	39.63

The impact of multiple passes on energy consumption

In this section, according to the pressure-sinkage data acquired from the bevameter and the calculation of the area below the pressure-sinkage curves, the cumulative energy consumption of each experiment was extracted in the range of 0-15, 0-30, 0-45, and 0-60 mm of plate sinkage into the soil.

Fig**. 8.** Effect of multiple passes on energy consumption in different depths and constant penetration rate for the 70 × 175 plateFig. 8 illustrates the variation in energy required for the penetration of the large plate into the soil at different depths, corresponding to various penetration rates.

As illustrated in the figure, the general trend in penetration energy for the large plate penetration is similar to that of the small plate. However, as expected, the energy consumption is significantly higher for the large plate due to its larger surface area and higher soil penetration resistance.

The Analysis of Variance (ANOVA) examining the effect of parameters on energy consumption at a fixed penetration rate, using a completely randomized design, is presented in Table 4. The results indicate that the number of passes has a statistically significant effect on energy consumption across all depth intervals for both plate sizes. Significance was determined at the 1% level for most depths, except the 15 mm sinkage depth of the small plate, where significance was observed at the 5% level.

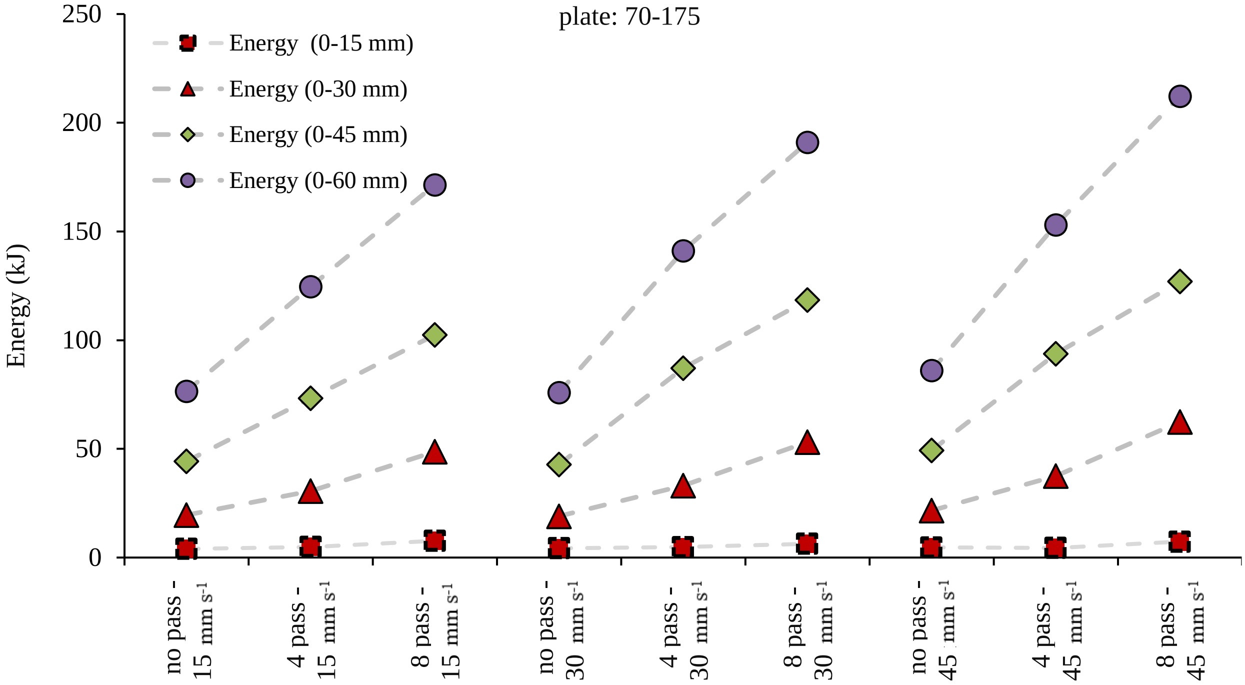

Fig. 8. Effect of multiple passes on energy consumption in different depths and constant penetration rate for the 70 × 175 plate

The impact of penetration rate on energy consumption

Although various approaches exist to account for the penetration rate in the Bekker equation (Grahn, 1996), there is limited information regarding its effect on the pressure-sinkage relationship. To address this gap, a modified bevameter was used to control the penetration velocity in a soil bin. Tests were conducted at different plate velocities, as outlined in Table 2. This section examines the effect of penetration velocity on energy consumption under constant traffic conditions, focusing on its influence through the pressure-sinkage relationship.

As demonstrated in Figures Fig. 9 and Fig. 10, changes in penetration rate (15 mm s^{-1}, 30 mm s^{-1}, and 45 mm s^{-1}) significantly influence energy consumption. With increasing speed, the energy required to achieve the same level of sinkage increases. This is likely due to the higher resistance generated between the plate and the soil at higher penetration rates, leading to increased energy expenditure. This trend is evident across both plate sizes. However, the larger plate (70 x 175 mm) exhibits a more pronounced increase in energy consumption as penetration rate and pass levels rise. For instance, at the 8th pass and a velocity of 45 mm s^{-1}, the energy consumption by the larger plate is nearly double that of the smaller plate under the same conditions, for a sinkage depth ranging from 0 to 60 mm. Similar results are reported by Apfelbeck *et al.* (2011).

Conclusion

The present study corroborates earlier findings regarding the influence of passes and penetration velocity on energy loss. The results reveal that traffic load and velocity are key factors in determining the pressure and energy required for soil penetration. Increased traffic leads to greater soil compaction, making the terrain more resistant to further deformation and requiring higher energy input, especially at higher speeds. The larger plate size (70 × 175 mm) consistently consumed more energy compared to the smaller plate (70 × 105 mm), indicating that surface contact area plays a crucial role in the interaction dynamics.

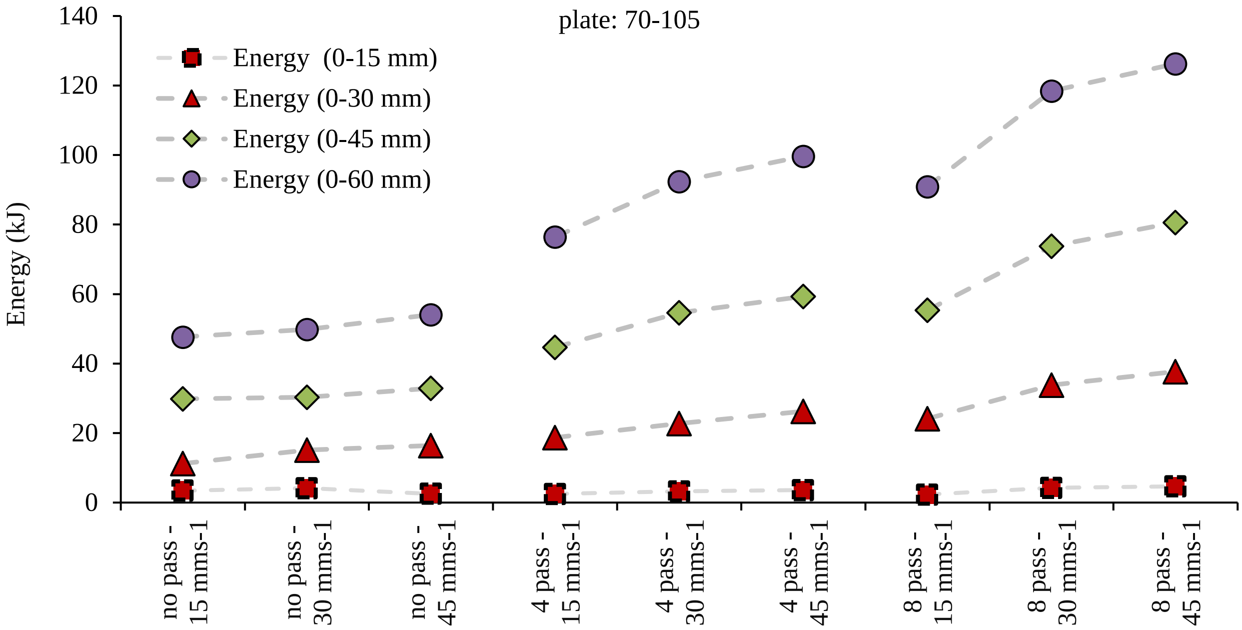

Fig. 9. The effect of penetration velocity on energy consumption in constant traffic in specified intervals, and constant traffic on the 70 × 105 plate

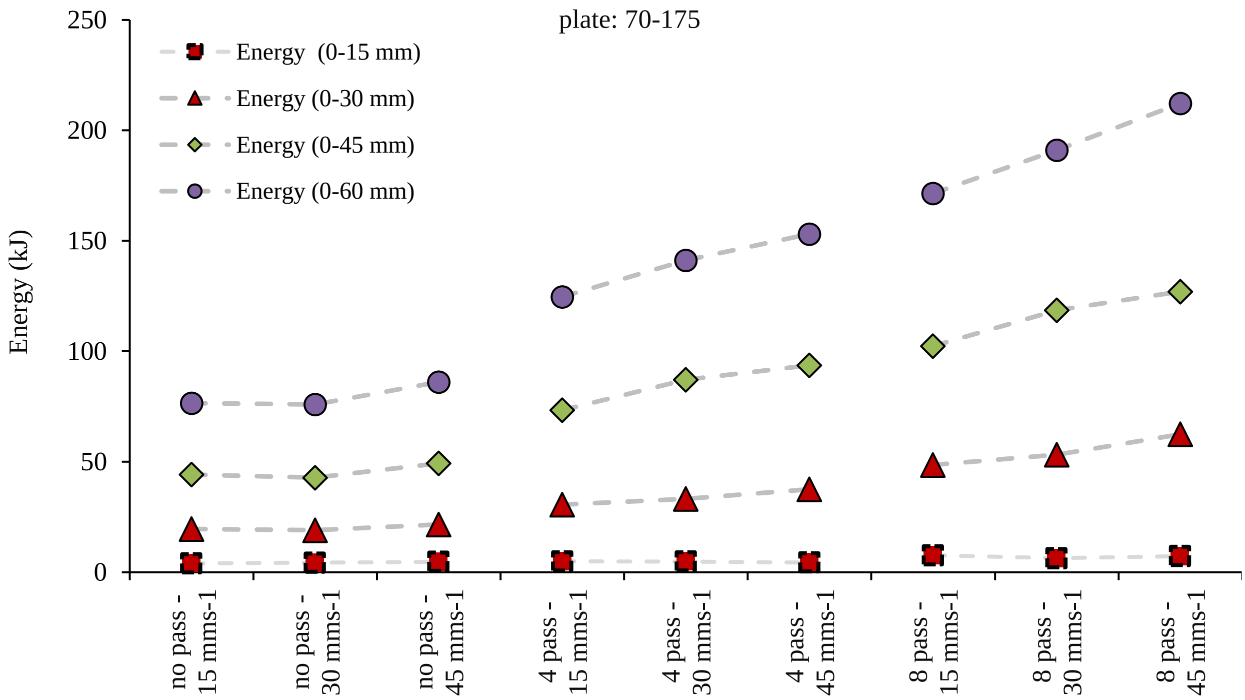

Fig. 10. The effect of penetration velocity on energy consumption in constant traffic in specified intervals, and constant traffic on the 70 × 175 plate

These findings are essential for optimizing vehicle performance in off-road environments, where minimizing energy consumption is crucial for efficiency. The study also provides valuable insights for soil management practices, particularly in agriculture and construction, where mitigating the negative effects of soil compaction is important. Future research could explore the long-term effects of repeated traffic and higher speeds on soil properties, contributing to the development of more sustainable land-use strategies.

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Conflict of Interest: The authors declare no competing interests.

Authors Contribution

H. Asadollahi: Methodology, Conceptualization, Data collection, Data processing, Extraction, and Preparation of the original text

B. Mohammadi-Alasti: Supervision and management, Conceptualization, Methodology, Validation, Text editing

A. Mardani: Supervision and management, Conceptualization, Validation, Text editing, Methodology, Technical advice

M. Abbasgholipour: Methodology, Technical advice, Statistical analysis, Visualization of results, Text editing

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ارزیابی تاثیر نرخ تغییر شکل خاک برای تخمین مصرف انرژی برهمکنش خاک و تایر با استفاده از رابطه فشار-نشست خاک

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چکیده

درک دینامیک تغییر شکل خاک در زمینه‌های مختلف مانند تحرک وسایل نقلیه خارج از جاده، کشاورزی و مکانیک خاک بسیار مهم است. به‌طور خاص، ارزیابی فعل و انفعالات خاک و تایر برای بهینه‌سازی مصرف انرژی و به حداقل رساندن اثرات منفی تراکم خاک ضروری است. این مطالعه تأثیر نرخ تغییر شکل خاک بر رابطه فشار- نشست و مصرف انرژی را با استفاده از یک محیط انباره خاک و یک سیستم بوامتر بررسی می‌کند. هدف اصلی این مطالعه بررسی این است که چگونه سطوح مختلف عبور و نرخ‌های نفوذ متفاوت بر انرژی مورد نیاز برای دستیابی به عمق نشست مشخص تأثیر می‌گذارند. این مطالعه از یک طرح بلوک کاملا تصادفی استفاده کرد که هر تیمار سه بار تکرار شد تا از دقت و قابلیت اطمینان، اطمینان حاصل شود. اندازه‌گیری‌های کمی با استفاده از یک لودسل متصل به بوامتر انجام شد. نتایج نشان داد که سطح ترافیک و سرعت نفوذ بر مقاومت خاک و مصرف انرژی تأثیر معناداری دارد. برای صفحه بزرگتر، فشار مورد نیاز برای نفوذ با سرعت‌ها و سطوح عبور بالاتر افزایش می‌یابد. در بالاترین سرعت (۴۵ میلی‌متر بر ثانیه) و عبور هشتم، نیروی مورد نیاز برای نشست خاک حداکثر بود. مصرف انرژی برای هر سطح با اندازه‌گیری سطح زیر منحنی نیرو- نشست محاسبه شد. تجزیه و تحلیل واریانس (ANOVA) نشان داد که تعداد عبور چرخ، اندازه صفحه و سرعت نفوذ به‌طور قابل‌توجهی بر مصرف انرژی تأثیر می‌گذارد. به‌عنوان مثال، در بالاترین عمق نشست (۶۰ میلی‌متر)، مصرف انرژی برای صفحه بزرگ‌تر با سرعت ۴۵ میلی‌متر بر ثانیه و عبور هشتم تقریبا دو برابر صفحه کوچک‌تر بود. این نتایج بر اهمیت در نظر گرفتن تراکم و سرعت ناشی از تعداد عبور در هنگام طراحی وسایل نقلیه خارج از جاده یا ماشین‌های کشاورزی که با زمین‌های تغییر شکل‌پذیر تعامل دارند، تأکید می‌کند.

واژه‌های کلیدی: انرژی تغییر شکل خاک، بوامتر، عبورهای متعدد، مکانیک خاک، نرخ نفوذ

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