Laboratory assessment of the effects of straw mulch on soil compaction under static and dynamic loads

Xianliang Wang[1*], Mingyue Bai[1], Jin He[2], Xiangcai Zhang[1], Kaihua Liu[3], Lei Liu[1], Shang Gao[1], Hong Hu[4], Jiangtao Ji[5]

(1. *College of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo 255000, China*;
2. *College of Engineering, China Agricultural University, Beijing 100083, China*;
3. *Guangdong Institute of Modern Agricultural Equipment, Guangdong Province Department of Agriculture and Rural Affairs, Guangzhou 510630, China*;
4. *Institute of Modern Agricultural Equipment, Xihua University, Chengdu 610039, China*;
5. *College of Agricultural Equipment Engineering, Henan University of Science and Technology, Luoyang 471023, China*)

Abstract: While straw mulching has been recognized for mitigating compaction, the multifactorial effects of straw parameters (content, length, laying modes) under static versus dynamic loads remain poorly quantified. Straw mulching may alter the stress transfer in the soil when applying static or dynamic loads. This study systematically evaluated stress and energy dissipation mechanisms using laboratory simulations: a plate sinkage test and an adapted Proctor test. The results demonstrated that the straw content (0-20 Mg/hm^2) dominantly governs dissipation efficiency, with maximum stress dissipation ratios of 45.6% (static load >200 kPa) and energy dissipation ratios of 38.64% (dynamic high-energy). Longer straw (0.20 m) and ordered laying modes enhanced stress dispersion only under low static loads, while dynamic loads exhibited weaker dissipation. The study reveals that the damping effect of straw is strongest under low stress static load, so it is necessary to reduce the compaction of agricultural machinery and optimize the allocation of straw, such as 15-20 Mg/hm^2, to alleviate compaction in clay loam soils. These findings can provide actionable insights for designing straw-based soil conservation strategies and improving compaction prediction models in mechanized agriculture.

Keywords: adapted Proctor test, agricultural engineering, soil compaction, straw mulching, stress dissipation
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1 Introduction

With the increasing utilization of large-scale agricultural equipment, mechanical compaction at the soil surface has emerged as a prominent issue, restricting the advancement of no-tillage technology[1-3]. However, the straw layer formed by crop residues on the soil surface possesses the potential to dissipate the loads generated by agricultural machinery operations, thereby partially reducing soil compaction[4-7]. The straw layer covering the soil surface also maintains the physical properties of soil to a certain extent by regulating soil water and gas exchange[8-10]. So, it is crucial to elucidate the impact of straw mulching on mechanical soil compaction to leverage the benefits of no-tillage technology and maintain the sustainability of agricultural soils[11-13].

Considerable research has been conducted on straw's effect on the potential load dissipation. Previous studies have confirmed straw's role in reducing compaction through uniaxial compression tests[4] and energy absorption analyses[14], yet critical gaps persist. Theoretical frameworks for straw-mediated stress dissipation often oversimplify soil-straw interactions. Most research isolates individual straw factors like the presence and absence of straw mulch or the content, neglecting interactions between parameters (content-length-laying modes) that likely govern real-world performance. For example, Reichert et al.[15] utilized an adapted Proctor test to comparatively analyze the difference between the presence and absence of straw mulch, confirming the ability of straw to absorb a portion of the compaction energy applied to the soil. Additionally, following previous studies of effects on soil compaction with and without corn residue, Cherubin et al.[16] analyzed the impact of different straw contents on the compaction dissipative effect. However, it remains unclear whether the factors, including straw contents, straw lengths, the straw-laying modes on the surface, and their interactions, affect soil compaction under static and dynamic loads in laboratory.

To test these hypotheses, two standardized methods were integrated: a plate sinkage test (static) and an adapted Proctor test (dynamic), quantifying stress transmission coefficients (*STC*) and energy dissipation ratios (ω_{Ed}) across straw configurations. Based on existing studies, Dawidowski et al.[17] proposed a method for

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Biographies: Mingyue Bai, MS Candidate, research interest: agricultural engineering, Email: 22403010019@stumail.sdut.edu.cn; **Jin He**, PhD, Professor, research interest: conservation tillage, Email: hejin@cau.edu.cn; **Xiangcai Zhang**, PhD, Associate Professor, research interest: conservation tillage technology equipment, Email: zxcai0216@163.com; **Kaihua Liu**, PhD, Lecturer, research interest: soil dynamics, Email: kaihua.liu@phd.unipd.it; **Lei Liu**, MS Candidate, research interest: agricultural mechanization, Email: 22503030004@stumail.sdut.edu.cn; **Shang Gao**, MS Candidate, research interest: agricultural mechanization, Email: twelve4666@gmail.com; **Hong Hu**, PhD, Lecturer, research interest: conservation tillage, Email: huhong@mail.xhu.edu.cn; **Jiangtao Ji**, PhD, Professor, research interest: intelligent planting mechanization, Email: jjt0907@163.com.
***Corresponding author: Xianliang Wang**, PhD, Associate Professor, research interest: soil dynamics. Shandong University of Technology, Zibo 255000, Shandong, China. Tel: +86-15264311735, Email: wxl1990@sdut.edu.cn.

calculating and validating soil compaction strength values using data from the plate sinkage test. Raghavan et al.[18] developed a predictive model for soil compaction in the field by comparing a standard Proctor test with a field machine compaction test. Aragón et al.[19] considered the Proctor test as dynamic loading to study the relationship between maximum bulk density and organic carbon content. The stress exerted on the soil by the loading plate in the plate sinkage test is a uniform and constant downward pressure, which can be regarded as a static load on the straw and soil[17]. In contrast, the stress exerted on the soil by the hammer in the Proctor test is an instantaneously varying impact stress, and thus can be considered a dynamic load on the straw and soil[20]. Considering the laboratory feasibility of simulating the soil surface covered with straw, this study utilized two tests to compare the dissipative effects of corn straw mulching.

The objectives of this study were: 1) to evaluate the effect of corn straw mulch on stress dissipation in soil under static loading conditions by plate sinkage test; 2) to assess the effect of corn straw mulch on compaction energy dissipation in soil under dynamic compaction loads using laboratory Proctor test conditions; and 3) to compare the effectiveness of corn straw mulching in dissipating stress in soil under static and dynamic compaction loads.

2 Materials and methods

2.1 The soil and straw

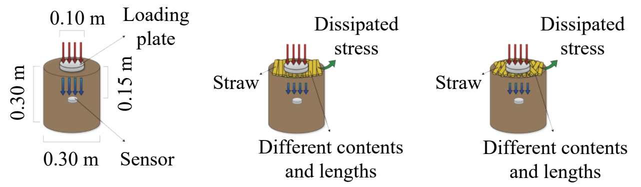
In this study, corn straw samples and soil samples were gathered from the no-tillage sowing experimental field in Xilu Village, Zibo City, Shandong Province (36°87′–36°88′N, 117°98′–119°99′E), where the annual precipitation is 655.8 millimeters. This area falls within the biannual maturing zone for wheat and corn in the Yellow and Huaihai Seas region. The soil type is clay loam, the soil moisture content ranged from 10% to 14%, and the soil bulk density was 1.25-1.55 Mg/m^3. During the corn harvest in September and October, corn straw samples were selected, with a diameter of 15±2 mm and moisture content of about 40%, excluding corn stubble, leaves, and the top portion of the straw. Soil samples were collected from the top layer (0-0.1 m) with a total weight of 30 kg, along with 10 kg of corn straw, and stored in airtight containers between trials to minimize moisture loss. The tests were conducted at 25°C and 60% relative humidity in laboratory.

2.2 Plate sinkage test

The soil samples were milled, submitted to a sieve of 30 mesh, and dried at 105°C for 24 h. Subsequently, the soil was moistened to achieve uniform moisture distribution, aiming for a moisture content of 12%. This ensured that the moisture content of the test soil samples closely matched the initial moisture content of the field soil (10%-14%).

Corn straw samples were cut into uniform strips with lengths of 0.10 m, 0.15 m, and 0.20 m. Four different mulching contents of 5, 10, 15, and 20 Mg/hm^2 were set to each of the three lengths of straw, respectively. Two types of straw mulching, ordered and disordered straw-laying modes, were employed. A control experiment without straw mulching was conducted as well. The experimental procedure and setup are depicted in Figure 1.

The soil was placed in an iron bucket (Figure 2a) with a diameter of 0.3 m and a height of 0.3 m. The soil was homogenously remolded into soil with a density of 1.25 Mg/m^3 in two stages using a nylon plate with a diameter of 0.3 m and a thickness of 0.04 m. The stress sensor was positioned 0.15 m below the soil surface, corresponding to a depth of 0.15 m[21]. The treated straw on the soil surface was placed within the iron bucket to proceed with the test.



a. No straw b. Ordered straw-laying c. Disordered straw-laying

Figure 1 Process of plate sinkage test with different sets of straw contents, lengths, and laying modes

a. Iron bucket b. Microcomputer control universal testing machine

Figure 2 Instruments for plate sinkage test

Microcomputer control universal testing machine (Figure 2b) was utilized to simulate the loading process of agricultural machinery at the tire-soil interface. It was achieved by applying pressure to the straw and soil through a press plate with a diameter of 0.1 m and a thickness of 0.025 m, positioned at the center of the bucket. The loading plate steadily sank at a rate of 0.03 mm/s, with eight different stress values of 25, 50, 100, 200, 300, 400, 500, and 600 kPa. The static stress levels (25-600 kPa) were selected to represent the range of contact pressures exerted by modern agricultural machinery tires, which typically operate between 100-800 kPa depending on axle load and tire inflation pressure[22]. Each application of pressure lasted 60 seconds. The loading time setting closely approximates the actual conditions of agricultural machinery applying loads on the tire-soil interface[22]. After each pressure application, the change in soil stress was measured by sensors, and three repetitions of the experiment were conducted to collect test data. Incidentally, due to the load application limitation of the testing machine, the static load applied in the plate sinking test could only be within 600 kPa, so it was unable to study soil stress transfer under static loads exceeding 600 kPa in this test. However, the impact of straw on load-bearing capacity is negligible in enhancing soil resistance to compaction from machinery traffic, as the stress applied by vehicles in field operations can exceed 600 kPa[16,22].

2.3 Proctor test

In this study, the soil samples used in the Proctor test were the same as those in the plate sinkage test. Based on the adapted Proctor test method, a 2103.9 cm^3 percussive cylinder mold with an inner diameter of 0.152 m and a height of 0.116 m was employed to extract soil samples. A 2.5 kg compaction hammer with a height of 0.3 m was used to compact soil specimens. The percussive cylinder mold and the compaction hammer are both standard. An iron plate, cylindrical in shape, was positioned on the soil within the mold, and energy was applied to the center of the plate to ensure an even distribution of tamping energy across the entire soil surface. The iron plate had a diameter of 0.15 m (matching the inner diameter of the tamping cylinder of 0.152 m) and a thickness of 3 mm. Different numbers of tamping strokes were administered (15, 30, and 50), corresponding to energy levels of 53.3, 106.6, and 177.6 kJ/m³, respectively[15]. Similarly, as in the plate sinkage test, the dynamic compaction energies corresponded to field conditions where repeated passes of heavy machinery apply cumulative energy inputs of about 50-200 kJ/m³, ensuring laboratory-to-field relevance[23].

To utilize a compaction mold with a diameter of 0.152 m, the length of the corn straw had to be adjusted with two lengths (0.05 m and 0.10 m) to accommodate the size of the compaction cylinder. Each experiment was performed three times to ensure accuracy in assessing the impact of different corn straw arrangements on energy dissipation in the soil under dynamic loading.

After compacting, the soil sample was extracted using a sample ejector, then a portion of the soil from the center of the sample was collected to determine soil bulk density and moisture content. A soil compaction curve was then constructed based on the results of the Proctor experiments. From these compaction curves, the maximum bulk density and optimum moisture content produced by the soil under the three types of compaction energies were calculated. The maximum bulk density BD_{max}-energy equivalent Ec change curve is fitted by simplifying the equation[14,15], and the simplified equation is referred to as follows:

$$BD_{max} = a + b(Ec) + c(Ec)^2 \quad (1)$$

where, BD_{max} represents the maximum soil bulk density (Mg/m³), Ec denotes the compaction energy equivalent (kJ/m³), and a, b, and c represent the fitting coefficients, respectively. The percentage (%) of soil energy dissipation corresponding to the straw mulch can be estimated by combining the maximum soil bulk density data obtained in the subsequent Proctor test with straw addition and applying the fitting equations to calculate the energy equivalent of each applied load.

3 Results and discussion

3.1 The measured stress under different straw mulching conditions in plate sinkage test

As illustrated in Figure 3, the lowest stress values, indicating the most significant effect of stress dissipation, were recorded when the straw content was 20 Mg/hm². At lower stress levels (<200 kPa), the average percentage of stress dissipation was 32.5%, while at higher stress levels (>200 kPa) ranging from 200 to 600 kPa, the maximum stress dissipation rate was 45.6%. This indicated that the content of straw had a great influence on the stress dissipation in soil.

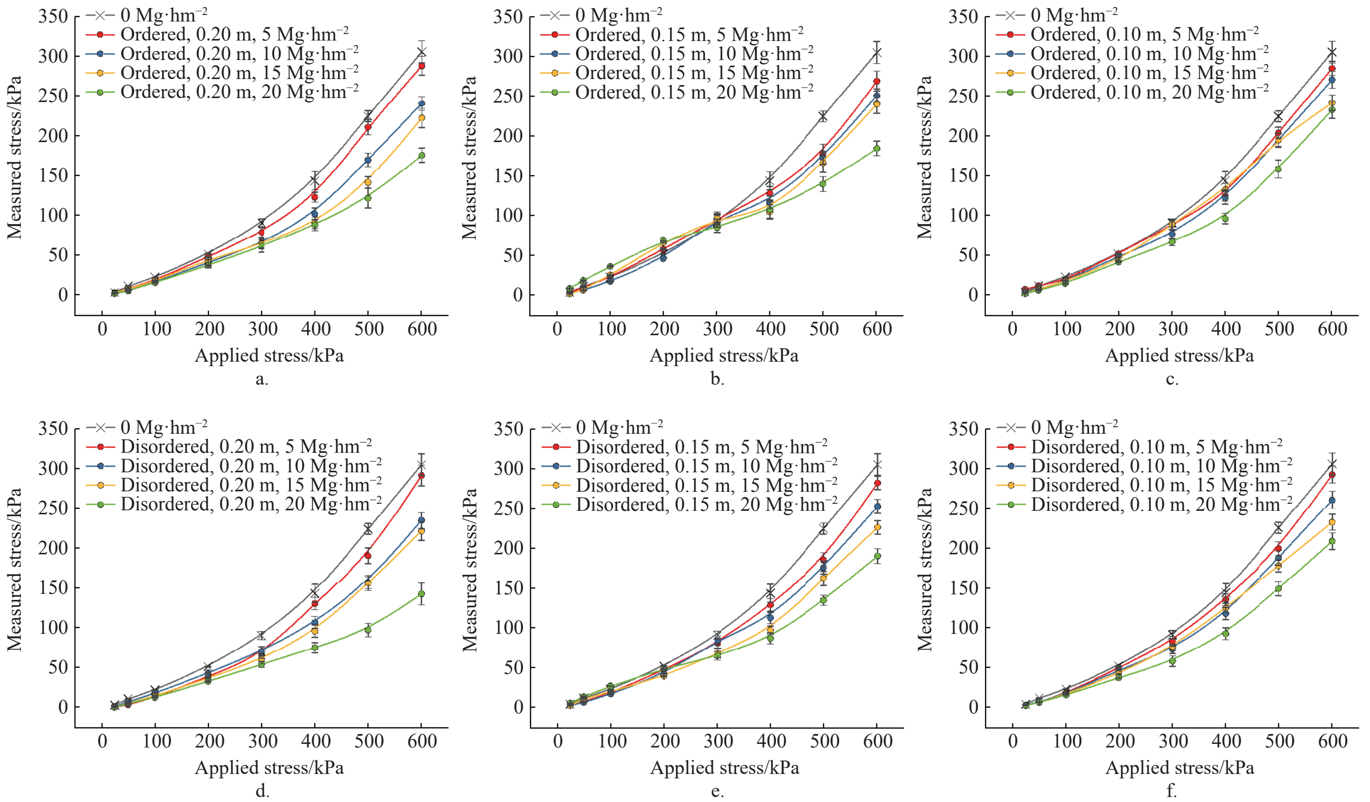


Figure 3 Comparison of measured-applied stress relationships at 0.15 m depth under different straw mulch: (a-c) ordered straw-laying mode and (d-f) disordered straw-laying mode, with each fig representing a different set of straw lengths and content. The bars show the standard error of replications.

However, it is shown in Figure 3 that the variation in straw length, as well as the two modes of straw laying, also had some impact on stress transfer. When the straw content was minimal (5 Mg/hm²), the effect of changing straw length on stress transfer was not as pronounced. The effect of straw length became more apparent as the straw content increased, with measured stresses gradually decreasing with increasing straw length.

On the other hand, the 0.15 m length of straw increased the value of the measured stress at lower stress levels (<200 kPa), and acted as a stress dissipator at higher stress levels (>200 kPa), with an average stress dissipation ratio of 34.8%, which may be related to the elastoplastic deformation properties of straw and soil[16,24].

3.2 Discussion

3.2.1 Maximum bulk density BD_{max} (Mg/m³) and energy dissipation ω_{Ed} (%) of soil in Proctor test

Figure 4 shows the trend of maximum dry bulk density (BD_{max}) of the control soil (no straw mulch) in the Proctor test, influenced by the compaction energy (Ec), indicating that soil bulk density increased with increasing compaction energy. The BD_{max} data obtained from the test was substituted into the fitting equation to derive the equivalent soil compaction energy with straw mulch and estimate the corresponding percentage energy dissipation ω_{Ed}.

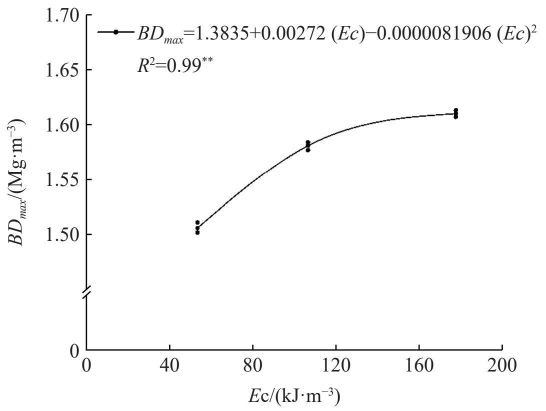


Figure 4 Fitting model equation of the change of the maximum dry bulk density BD_{max} with the compaction energy Ec of soil without straw cover after compacting in the Proctor test (**The adjusted model was significant when $p\leq0.01$)

Table 1 presents the results of the Proctor test, where the maximum energy applied to the soil surface in the absence of straw mulch (0 Mg/hm²) was 177.6 kJ/m³ (50 blows), resulting in a maximum dry bulk density (BD_{max}) of 1.63 Mg/m³. ANOVA revealed that straw content significantly influenced ω_{Ed} ($p<0.05$), whereas straw length and laying modes showed no statistically meaningful effects ($p>0.1$), and there was no interaction effect between the variables. The lack of interaction effects ($p>0.05$) suggests that straw parameters act independently under dynamic loading, contrasting with static conditions where interactions were observed.

Table 1 Maximum bulk density BD_{max} (Mg·m⁻³) and energy dissipation ω_{Ed} (%) under different corn straw mulch in the adapted Proctor test

Straw-laying modes	Straw lengths/ m	Straw contents/ Mg·hm⁻²	Blows 15 BD_{max}/ Mg·m⁻³	15 ω_{Ed}/ %	30 BD_{max}/ Mg·m⁻³	30 ω_{Ed}/ %	50 BD_{max}/ Mg·m⁻³	50 ω_{Ed}/ %
None	0	0	1.52	0.00	1.60	0.00	1.63	0.00
Ordered	0.05	5	1.49	11.98d	1.56	18.75c	1.59	23.32bc
		10	1.48	19.74c	1.55	27.13bc	1.58	31.18b
		15	1.47	25.35bc	1.53	32.47b	1.56	36.72a
		20	1.45	31.86b	1.52	35.68ab	1.54	37.78a
	0.10	5	1.47	13.2d	1.56	19.99c	1.59	24.81bc
		10	1.48	19.49c	1.54	26.96bc	1.57	30.02b
		15	1.4	26.61bc	1.53	31.39b	1.55	37.09a
		20	1.46	29.09b	1.52	34.28ab	1.54	38.35a
Disordered	0.05	5	1.48	11.42d	1.55	20.44c	1.59	22.81c
		10	1.47	20.95c	1.54	27.26b	1.57	29.74b
		15	1.47	27.63bc	1.53	32.27b	1.55	36.35ab
		20	1.45	30.17b	1.51	35.39ab	1.53	38.51a
	0.10	5	1.48	12.07d	1.55	20.29c	1.58	22.53c
		10	1.47	22.06c	1.54	28.32b	1.57	30.24b
		15	1.46	26.48bc	1.53	32.81b	1.55	35.63ab
		20	1.45	29.24b	1.51	34.84ab	1.53	38.64a

Note: Means followed by the same letter did not differ between depths by the Tukey test at the 0.05 probability level.

At lower compaction energy (53.3 kJ/m³), it is observed from Table 1 that energy dissipation from straw mulching increased with the rise in straw content, manifesting a more pronounced buffering effect of straw. Conversely, under high-pressure energy (177.6 kJ/m³), soil energy dissipation occurred when the highest content (20 Mg/m³) of straw mulching with the highest energy dissipation ratio reached 38.64% with a standard error of ±0.02 Mg/m³, confirming content as the dominant factor. However, the decrease in energy dissipation was only around 7% when compared to the condition with 20 Mg/m³ straw mulch. This finding aligns with the final results of the static plate sinkage tests conducted at high stresses, indicating that mulching a large content of straw dissipates dynamic and static loads at lower levels.

The models of energy dissipation (ω_{Ed}) with straw content (SC) are presented in Table 2. It is worth mentioning that the linear model fitted by the experimental results did not correspond to the real situation, and the quadratic model was the more ideal model. This is because the energy dissipation in the soil cannot increase infinitely with the increase of straw content but will reach a critical value[14], thus the quadratic model should be chosen.

Table 2 Energy dissipation ω_{Ed} models due to compression under different straw content (SC)

Ec/kJ·m⁻³	Model	R^2	p-value
53.3	$\omega_{Ed} = 1.3775 + 2.3995(SC) - 0.0482(SC)^2$	0.98**	<0.01
106.6	$\omega_{Ed} = 10.130\,62 + 2.191\,53(SC) - 0.047\,38(SC)^2$	0.99**	<0.01
177.6	$\omega_{Ed} = 13.036\,25 + 2.283\,95(SC) - 0.050\,55(SC)^2$	0.98**	<0.01

3.2.2 Effects of different forms of corn straws on the stress transmission coefficient (STC) of soil under the plate sinkage test

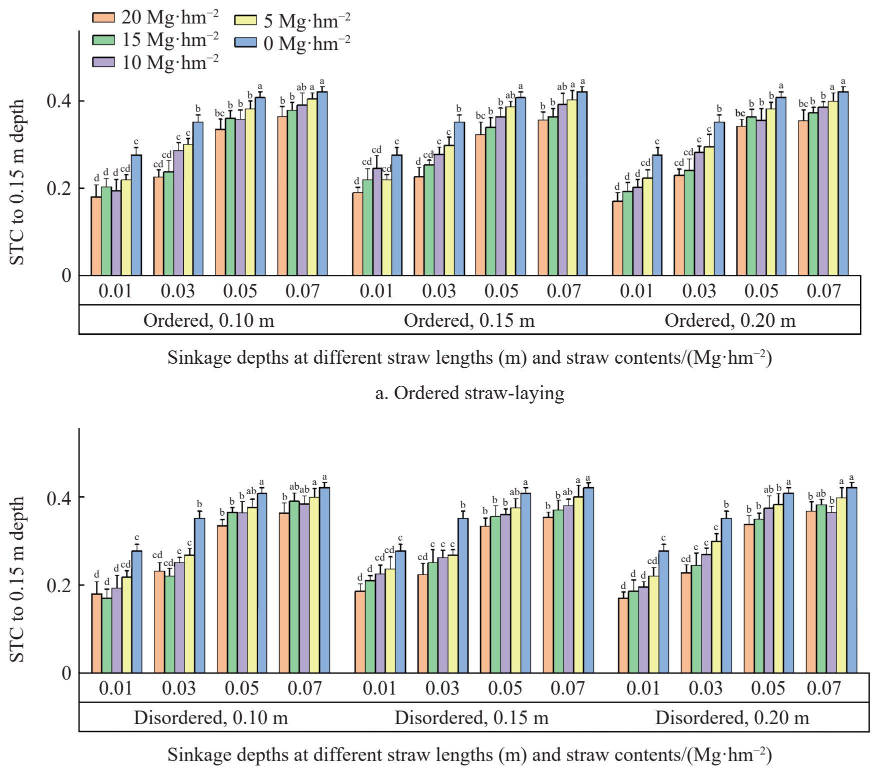
Figure 5 depicts the variation of the stress transmission coefficient (STC) with the four different depths of 0.01 m, 0.03 m, 0.05 m, and 0.07 m of the loading plate under different laying modes. According to He et al.[25], the formula for calculating the stress transmission coefficient (STC) was clearly defined as the ratio of measured soil stress (σ_z) to applied surface stress (σ_0):

$$\mathrm{STC} = \frac{\sigma_z}{\sigma_0} \tag{2}$$

STC was defined as an index that helped to compare the stress transfer of soil under the influence of straw mulch when the loading plate sank into different depths; this research demonstrated that STC for a given soil is constant. However, it is observed in Figure 5 that when there was no straw cover (0 Mg/hm²), soil STC increased with the sinking depth. This disparity may arise from different boundary conditions (lateral limit compression test versus plate sinkage test)[21,25].

Besides, the STCs under straw-soil interaction in the presence of straw cover were consistently lower than the STCs of pure soil in the absence of straw cover, indicating that the presence of straw affects stress transmission in the soil. The STCs of covered and no straws were significantly different ($p<0.05$) under the smaller sinking depth of the loading plate (0.01-0.03 m), while they were not significantly different ($p>0.05$) under the larger sinking depth of the loading plate (0.05-0.07 m).

Under the same sinking depth of the loading plate, variations in straw content had a significant effect ($p<0.05$) on STC. Theoretically, the vertical stress transfer in soil subjected to static loading of straw and soil decreases with increasing straw content due to the damping effect of the straw[26-28]. Nevertheless, the effect of straw content cannot be explained solely by the theory that the straw layer reduces the propagation of stresses reaching the soil surface. Rather, it is also related to the materiality of the straw and soil[24]. The amount and thickness of the straw layer directly affects the soil-wheel interface by increasing the contact area and reducing the stress propagation to soil[5].



a. Ordered straw-laying

b. Disordered straw-laying

Figure 5 The stress transmission coefficient (STC) to 0.15 m depth under different straw mulch modes (Means followed by the same letter did not differ between depths by the Tukey test at the 0.05 probability level)

In light of this, the hypothesis was that different kinds of corn straw, including differences in content, length, laying modes, and the interaction of the multiple factors mentioned above, had a certain effect on the stress transfer in the soil; this hypothesis was confirmed here. Longer straws might come into contact with more soil particles, increasing the physical contact area between the straw and the soil, thereby slowing down the concentration of stresses and aiding in relieving soil compaction[30]. Straw-laying modes could also influence the direction of stress transfer in the soil. For instance, the horizontal mulching method of straw might cause stress transfer in the horizontal direction, while the vertical mulching method might lead to stress transfer in the vertical direction. This change could alter the stress transfer path in the soil and reduce the rate of stress transfer, potentially mitigating soil compaction[31].

The test data did not fully explain the complex interactions between straw and soil compaction, and it is expected that researchers will follow up with better laboratory experiments or mathematical models to explore the interactions between straw and soil in depth. Therefore, later studies are necessary to model the interaction between stress, straw, and soil contact to elucidate the complex interactions between straw and soil compaction states from a microscopic perspective.

3.2.3 The dissipation effect of corn straw under static and dynamic loads

Based on the laboratory plate sinkage test and Proctor test, it was observed that corn straw exhibited a more significant dissipation effect under the static load. It was hypothesized that this might be due to the significant variability and strong shock nature of the dynamic loads applied to the soil in the Proctor test, leading to soil vibrations and stress concentrations[23]. The transient and intense nature of the dynamic loading resulted in the soil not being able to adapt adequately, leading to the energy of the dynamic loading not being sufficiently absorbed and dispersed by the straw[32]. As discussed by Reichert et al.[15], laboratory results typically surpass those obtained from field tests, attributed to the fact that Proctor test results are derived from laboratory unstructured soils, theoretically heightening soil compaction sensitivity. Besides, longer straw (0.20 m) and ordered laying modes enhanced stress dispersion only under low static loads, while dynamic loads exhibited weaker dissipation. It is hypothesized that this is due to the ordered straw-laying mode's likely creation of a uniform stress distribution network through aligned fibers, redirecting vertical stresses laterally. In contrast, disordered straw forms irregular voids, concentrating stresses locally. This aligns with DEM studies by Liu et al.[28], where aligned fibers enhance stress dispersion via frictional interactions.

From this, it was concluded that under low-stress conditions, corn straw performed better under static loading, and its dissipation effect was more significant. Under dynamic loading, the dissipation effect of straw was relatively weak due to the different nature of impacts, and it could not completely offset the effects of dynamic loading. However, in both dynamic and static compaction, the energy dissipation provided by straw became negligible when the compaction energy was large enough.

4 Conclusions

The effect of mulching with a large content of straw (20 Mg/m^3) on dissipating static and dynamic loads under high stress or high energy levels is consistent. The attainable maximum percentage of dissipation under static loading at higher stress levels (>200 kPa) was 45.6%, while under dynamic loading with high compaction energy (177.6 kJ/m^3) it was 38.64%. Nevertheless, when the compaction action was large enough, all the energy dissipation of straw on the soil surface became negligible.

The average stress dissipation percentage of corn straw at lower stress levels (<200 kPa) was 32.5%, which was more obvious. Longer straw and ordered laying modes enhanced stress dispersion under low static loads. However, the effect of straw dissipation under dynamic loading at low stresses was weaker, and the energy dissipation ratios were all lower than the stress dissipation ratios in static loading under the same straw conditions.

In the end, laboratory tests and field experiments of different soil types, straw configurations, and mechanical operating conditions should be further conducted in future studies to establish mathematical models of stress-straw-soil interaction, in order to understand the effects of straw in different soil environments and to optimize agricultural machinery and farmland management strategies carefully and comprehensively.

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