DESIGN AND TESTING OF ULTRASONIC GAS-LIQUID TWO-PHASE JET SUBSOILING MACHINE
/
超声波激振气液两相射流深松机设计及试验

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ABSTRACT
To address the challenges of high tillage resistance, high energy consumption, and suboptimal subsoiling performance associated with soil compaction management and conventional subsoiling operations, this study integrates gas-liquid two-phase jet soil-breaking technology with ultrasonic vibration drag reduction technology to design and develop an ultrasonic vibration-assisted gas-liquid two-phase jet subsoiler. With a subsoiling depth of 30 cm and an operating speed of 3 km/h selected as standard test conditions, a systematic investigation of the subsoiler's operational performance was conducted using simulation modeling, soil bin tests, and field experiments. The study examined the variations in tillage resistance, soil disturbance area, and soil porosity. Experimental results indicate that, compared with conventional mechanical subsoiling, the combined application of ultrasonic vibration and gas-liquid two-phase jet reduces tillage resistance by 17.5% and increases the soil disturbance area by 7563.3 mm². At a soil depth of 30 cm and a horizontal width of 30 cm, the maximum increase in soil porosity reaches 0.115 mm. Comprehensive analysis demonstrates that the ultrasonic vibration-assisted gas-liquid two-phase jet subsoiling technology significantly reduces tillage resistance, enhances soil disturbance, and improves soil pore structure, thereby offering a new technological solution for low-drag, high-efficiency subsoiling operations.

摘要
针对土壤压实治理与传统深松作业存在的耕作阻力大、作业能耗高、深松效果欠佳等问题，本研究融合气液两相射流破土与超声波激振减阻技术，设计并搭建了一款超声波激振气液两相射流深松机。选取深松深度 30 cm、作业速度 3 km/h 为标准试验工况，采用仿真模拟、土槽台架试验与田间实地试验相结合的方法，系统测试并分析该深松机的作业性能，探究其耕作阻力、土壤扰动面积及土壤孔隙度的变化规律。试验结果表明，相较于传统机械深松方式，超声波激振与气液两相射流的组合深松技术，可使耕作阻力降低 17.5%，土壤扰动面积增大 7563.3 mm²。在土层深度 30 cm、水平宽度 30 cm 处，土壤孔隙度最大提升量达 0.115mm。综合分析表明，超声波激振气液两相射流复合深松技术能够显著削减耕作阻力、优化土壤扰动效果、改善土壤孔隙结构，为低阻高效土壤深松作业提供了新的技术方案。

INTRODUCTION
Although the extensive use of modern agricultural machinery has improved production efficiency, it is easy to lead to soil compaction and the formation of hard soil layer *(Ahmadi, 2017; Ren et al., 2022)*, which will reduce soil aeration and water permeability, and limit the growth of plant roots and nutrient absorption *(Shah et al., 2017; Tracy et al., 2011)*. As a kind of conservation tillage, subsoiling can loosen the soil by breaking compacting the soil layer and improving the granular structure, thus enhancing the permeability and water infiltration capacity *(Sun et al., 2018)*. subsoiling not only helps plant roots to grow downward and absorb more water and nutrients, but also improves the water retention capacity of the soil *(Martínez et al., 2012)*.

Current subsoiling techniques primarily include bionic subsoiling, vibrational subsoiling, and pneumatic subsoiling. Among these, bionic subsoiling enhances soil quality and reduces operational resistance by emulating specific biological characteristics found in nature *(Sanchez et al., 2005)*. For example, *Wang et al., (2020)* designed a bionic shark deep pine machine, which utilized the ribbed structure of shark scales to assess tillage resistance, total energy consumption, and soil disturbance. Drawing on the digging ability of hares, *Zhao et al., (2023)* designed a bionic energy storage device, and field tests showed that its deep pine energy consumption was 16.2% lower than that of conventional devices. Vibration deep loosening loosens soil through vibration mechanical devices. *Wang et al., (2019)* The interlaced vibration mechanism developed shows better working performance. Pneumatic deep-pine increases soil porosity and improves water infiltration capacity through pneumatic equipment. *Zuo et al., (2016)* proposed a subsoiling method based on pneumatic split technology. *Li et al., (2022)* The designed pneumatic deep loosening mechanism can effectively reduce resistance.

The combination of ultrasonic excitation and gas-liquid two-phase jet deep loosening not only reduces the tillage resistance during deep loosening operations but also increases the disturbance to the soil and soil porosity. *Liu et al., (2023)* experimentally compared the impact effects of a traditional water jet and a gas–liquid two-phase jet, showing that the introduction of air significantly improves the material removal rate. *Shi et al., (2023)* proposed a gas-liquid two-phase jet cleaning technique, demonstrating that the impact pressure and material removal efficiency vary significantly with distance. *Cheng et al., (2025)* proposed a resistance reduction method for ultrasonic vibration-assisted cutting, providing a new research direction for the development of resistance reduction equipment in agricultural tillage operations. *Wang et al. (2020)* designed an ultrasonic high-frequency vibration-assisted soil cutting and excavation device to reduce resistance, addressing the issues of high operational resistance and high energy consumption of agricultural machinery soil-contacting components. The device achieved resistance reduction rates of 35.1%, 40.7% and 44.3% under soil hardnesses of 1.5, 2.5 and 3.5 MPa, respectively. *Wang et al., (2021)* investigated the influence of ultrasonic vibration on the interaction between the touching parts of agricultural machines and the soil, revealing that ultrasonic vibration significantly reduces the working resistance.

This study proposes ultrasonic-excited gas-liquid two-phase jet subsoiling to address the issues of high tillage resistance and poor subsoiling effect during subsoiling operations. This study designed a subsoiling machine combining ultrasonic excitation and gas-liquid two-phase jet. Through simulation tests and field tests, the tillage resistance and soil disturbance area of the ultrasonic excitation gas-liquid two-phase jet subsoiling machine were comprehensively analyzed and verified. The soil trough test verified the influence of ultrasonic excitation gas-liquid two-phase jet subsoiling on soil porosity. The main purpose is to verify whether the ultrasonic-excited gas-liquid two-phase jet subsoiling machine can achieve drag reduction and subsoiling improvement effects compared with other subsoiling machinery.

MATERIALS AND METHODS

Structural design of the machine

The structure of the ultrasonic-excited gas-liquid two-phase jet subsoiling machine is illustrated in Fig 1. The main components consist of a booster pump, a water tank, an air compressor, and an ultrasonic generator. This machine is connected to a tractor via a three-point suspension system, utilizing the tractor's power for driving and traction during operation. The principal technical specifications of the subsoiling technique incorporating ultrasonic vibration and a gas-liquid two-phase jet are presented in Table 1. Both the booster pump, water tank, ultrasonic generator, and the air compressor are installed above the frame. The air compressor generates high-pressure gas, while the booster pump elevates the water pressure. The ultrasonic generator ensures the uniform mixing of gas and liquid, and causes the sub-soiling shovel to vibrate at a high frequency. The air compressor is connected to the inlet of the gas-liquid mixer through a pipeline. One end of the booster pump is connected to the water tank, and the other end is connected to the water inlet of the gas-liquid mixer. The outlet pipeline of the gas-liquid mixer is connected to the sub-soiling shovel, and a nozzle is installed at the end of the pipeline. The oscillators of the ultrasonic generator are arranged at the sub-soiling shovel and below the gas-liquid mixer. The pulse controller controls the solenoid valve to achieve pulse output. The sub-soiling shovel is fixed to the rear crossbeam of the frame by U-shaped bolts. During the deep ploughing process, the gas-liquid two-phase jet is mixed evenly in the gas-liquid mixer and is transported through the pipeline to subsoiler point.

During subsoiling, a uniform pulse jet is sprayed out, and the ultrasonic generator causes the sub-soiling shovel to vibrate at a high frequency, assisting the subsoiler in completing the subsoiling operation and effectively loosening and crushing the soil.

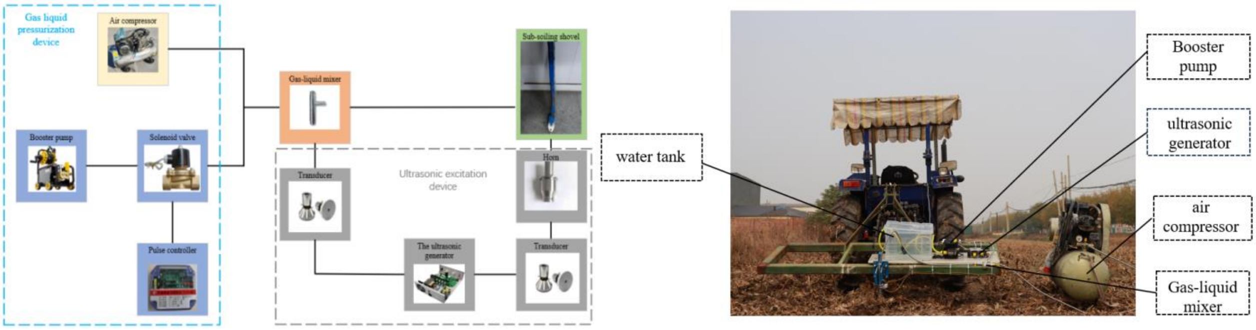


Fig. 1 - Whole structure

Table 1

Tractor parameter

Major component	Parameter
Booster pump pressure /MPa	10
Booster pump flow rate L/h	350
Water tank dimensions（mm×mm×mm）	600×700×400
Air compressor pressure /MPa	0.8
Air compressor flow rate (m3/min）	0.17
Frequency of ultrasonic generator /kHz	40
Power of ultrasonic generator /W	1500
Oscillator frequency /kHz	40
Oscillator power /W	100

Simulated test

The interaction between the subsoiler and the soil was simulated using EDEM (Discrete Element Method) and Fluent (computational fluid dynamics) software. In this study, a standard chisel-type subsoiler was selected, comprising a tip, a shank, wing plates, and connecting bolts. A full-scale three-dimensional model was developed using SolidWorks and subsequently exported in STEP format for further analysis. Within the EDEM environment, soil model parameters involving 65Mn steel as the contact material were established based on field soil conditions and relevant literature (*Baars, 2008; Zheng et al., 2016*), as summarized in Table 2. A stratified soil model was constructed within a simulation domain of 1500 mm (length) × 1500 mm (width) × 500 mm (height). The soil profile was divided into three layers from the surface downward: the plough layer (0-160 mm), the plough pan (1-280 mm), and the subsoil (280-500 mm), as illustrated in Figure 2.

Fig. 2 - Soil model

The EDEM-Fluent coupling method was employed to achieve a two-way coupled simulation between the particle system and the fluid medium. In EDEM, the subsoiler model was imported in STEP format, followed by the sequential configuration of particle and material parameters, assignment of motion parameters for the subsoiler, setting of the time step, and activation of the coupling server. In Fluent, a 3D double-precision solver was selected, and 8-core parallel computing was enabled to improve computational efficiency.

The mesh file was then imported, the unit system was unified, and the coupling connection with EDEM was established. Subsequently, the turbulence model, boundary conditions, and calculation parameters were configured. Once all settings were completed, the coupled simulation was executed.

To accurately simulate the actual subsoiling performance, the forward speed of the subsoiler was set to 3 km/h, and the working depth was set to 30 cm. During the simulation, the time step was set to 20% of the Rayleigh time step (i.e., 1.7×10^{-5} s), and the data storage interval was set to 0.01 s. Based on these simulation settings, the subsoiling resistance and soil disturbance characteristics under different subsoiling methods were compared and analyzed.

Table 2

Necessary parameters in EDEM

Parameter	Surface layer	Plough layer	Plow sole
Particle radius（mm）	3.5	3.5	3.5
Poisson ratio	0.3	0.3	0.3
Shear modulus（pa）	1.02e+08	1.02e+08	1.02e+08
Recovery coefficient	0.6	0.55	0.5
Static friction coefficient	0.45	0.4	0.35
Coefficient of rolling friction	0.3	0.28	0.25

Soil bin test

To eliminate interference from complex field conditions, validate the underlying mechanisms of subsoiling, and systematically evaluate the operational performance of the ultrasonic vibration-assisted gas-liquid two-phase jet subsoiling technology, a soil bin test was conducted in this study (Fig. 3). The stainless steel soil bin measured 80 cm in length, 80 cm in width, and 50 cm in depth. Soil preparation was carried out using the soil bin, a compaction roller, and an impact hammer. Soil samples were collected from the experimental field in Jinghai District, Tianjin (38.79°N, 117.01°E). The soil was backfilled layer by layer in accordance with the original stratification and compacted sequentially to preserve the natural soil profile. Additionally, the soil moisture content was adjusted to ensure consistency with field conditions in terms of both compaction and water content, thereby establishing a reliable soil foundation for the experiment.

Fig. 3 - Soil bin test scene

During the soil bin test, the following operational parameters were set: gas pressure of 0.8 MPa, liquid pressure of 0.3 MPa, ultrasonic generator operating frequency of 30 kHz, and amplitude of 20 μm. Four treatment conditions were applied sequentially: combined ultrasonic vibration-assisted gas-liquid two-phase jet subsoiling, gas-liquid two-phase jet subsoiling alone, ultrasonic vibration subsoiling alone, and pneumatic subsoiling alone. All treatments were performed under identical soil conditions. By measuring soil porosity within a fixed profile (width 50 cm, depth 30 cm) before and after each subsoiling operation, the improvement effects of the different subsoiling methods on soil aeration and permeability were compared and analyzed.

To evaluate the effects of different subsoiling methods on soil porosity, an improved Miller Soil Box was employed to measure soil electrical resistivity, and the measured data were combined with soil moisture content to estimate porosity. Specifically, following each subsoiling treatment, resistivity data were systematically collected within a 0.5 m range along the direction of operation.

Based on the average volumetric soil moisture content of 16.5% recorded in this experiment, a quantitative relationship between resistivity and porosity was established using the empirical model reported in the literature, resulting in a conversion relationship suitable for the soil conditions of this study (Equation 1).

$$\rho_0 = 0.102\varphi^{-5.006}\left[0.477\frac{(1-\varphi)}{\varphi}\right]^{-3.768} \tag{1}$$

where: ρ_0 represents soil resistivity and φ represents soil porosity.

The equation was solved by programming using the 1stOpt (Version 1.5) mathematical software, and the corresponding porosity values were calculated based on the resistivity measured at each test point. Resistivity data collected before and after different subsoiling treatments were input into the programmed model to determine the porosity at each sampling location. The obtained porosity values were then visualized as contour maps using Origin data analysis software, enabling a direct comparison of soil porosity variations under different subsoiling methods. This approach effectively illustrated the impact of each treatment on soil structure.

Field test

The field experiment was conducted at the experimental site in Jinghai District, Tianjin (38.79° N, 117.01° E). The terrain was flat, the previous crop was corn, and no subsoiling had been performed prior to the experiment. The experimental area was divided into 15 plots of equal size, each measuring 10 m in length and 6 m in width, covering a total area of 900 m². Five subsoiling treatments were established: gas-liquid two-phase jet subsoiling, ultrasonic vibration subsoiling, combined gas-liquid two-phase jet and ultrasonic vibration subsoiling, pneumatic subsoiling, and traditional mechanical subsoiling. All treatments were conducted at a uniform depth of 30 cm and a forward speed of 3 km/h. Each treatment was replicated three times, and the replicates were arranged in a randomized complete block design to minimize systematic errors and ensure the reliability of the experimental data.

The forward speed and working depth were maintained constant throughout the experiment. The draft force under each subsoiling method was measured using an S-type digital load cell (Model: DYY-103, range: 0-5 T). The load cell was installed between the tractor's three-point hitch and the subsoiler, converting mechanical force into an electrical signal transmitted to a high-speed data acquisition system. Equipped with multi-channel synchronous sampling and large-capacity storage capabilities, the acquisition system enabled continuous recording of dynamic resistance variations during field operations. Connected to a host computer (laptop) via a USB interface, the system, in conjunction with dedicated software, facilitated real-time data reception, dynamic curve visualization, and preliminary data processing. To eliminate interference from unstable measurements, data segments collected during the startup and deceleration phases were discarded. The average value over the stable middle section of the operation was taken as the representative draft force for each treatment. Outliers were identified and removed using the Grubbs' test criterion.

To investigate the effects of different subsoiling methods on soil disturbance characteristics, the "plank insertion + image processing" method was adopted to quantify the disturbed soil area. Within the stable operating section of the tractor, representative sampling zones were selected. Loose soil in the furrow was first removed to fully expose the actual profile created by the subsoiler. A flexible ruler was used to measure multiple points along the longitudinal direction of the furrow to determine the disturbance depth and lateral extent. Subsequently, the plank insertion method was employed by inserting vertical planks along the cross-section of the furrow into the soil; the resulting soil profile was traced onto the plank and then transferred to white paper. The projected area of the traced contour was calculated using ImageJ software to obtain the soil disturbance area for each subsoiling treatment. For each treatment, three profiles were measured, and both the mean and standard deviation were computed.

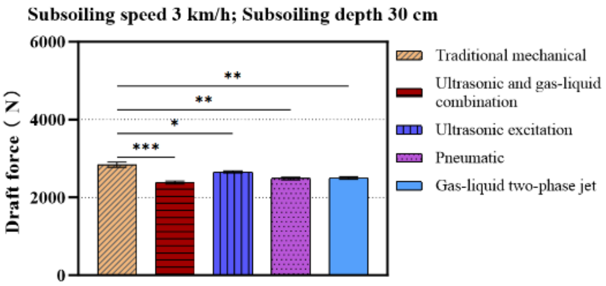
RESULTS

The influence of different subsoiling methods on tillage resistance

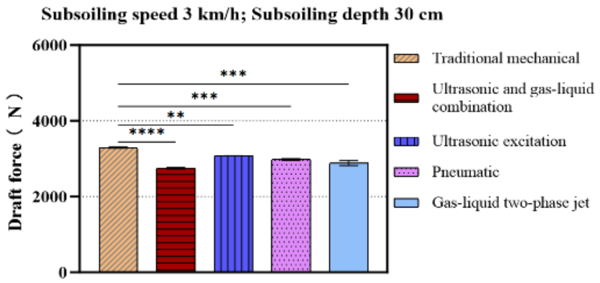
The tillage resistance of different subsoiling methods in simulation tests and field tests was compared to verify the drag reduction effect of different deep loosening methods. It was found that the tillage resistance of subsoiling by ultrasonic excited gas-liquid two-phase jet was the smallest. The simulation test results are shown in Fig. 4a. subsoiling of the gas-liquid two-phase jet by ultrasonic excitation (2353.9N)< subsoiling of the gas-liquid two-phase jet (2458.2N)< pneumatic subsoiling (2524.4N)< subsoiling by ultrasonic excitation

(2674.8N)< subsoiling by traditional machinery (2888.4N). Among them, the subsoiling tillage resistance of the combination of ultrasonic excitation and gas-liquid two-phase jet is the smallest, and the difference in resistance compared with the traditional mechanical subsoiling tillage is 534.5 N. The average tillage resistance in the field test is basically consistent with the simulation experiment results, as shown in Fig 4b. Ultrasonic excited gas-liquid two-phase jet subsoiling (2737.1N)< gas-liquid two-phase jet subsoiling (2836.0N)< pneumatic subsoiling (2997.6 N)< ultrasonic excited subsoiling (3074.5 N)< traditional mechanical subsoiling (3282.3 N). Among them, the subsoiling tillage resistance of the combination of ultrasonic excitation and gas-liquid two-phase jet is the smallest, and the difference in resistance compared with the traditional mechanical subsoiling tillage is 545.2 N.

By comparing the tillage resistance of the simulation experiment with that of the field experiment, it can be concluded that the tillage resistance of the simulation experiment is slightly lower than that of the field experiment, with an error of about 12%. The main reason is that the influence of crop roots was not considered in the simulation process. When comparing the tillage resistance of different deep loosening methods, the combination of ultrasonic excitation and gas-liquid two-phase jet deep loosening has the best drag reduction effect during the subsoiling process, reducing it by 17.5% compared with traditional mechanical subsoiling.



(a) Simulation test of tillage resistance



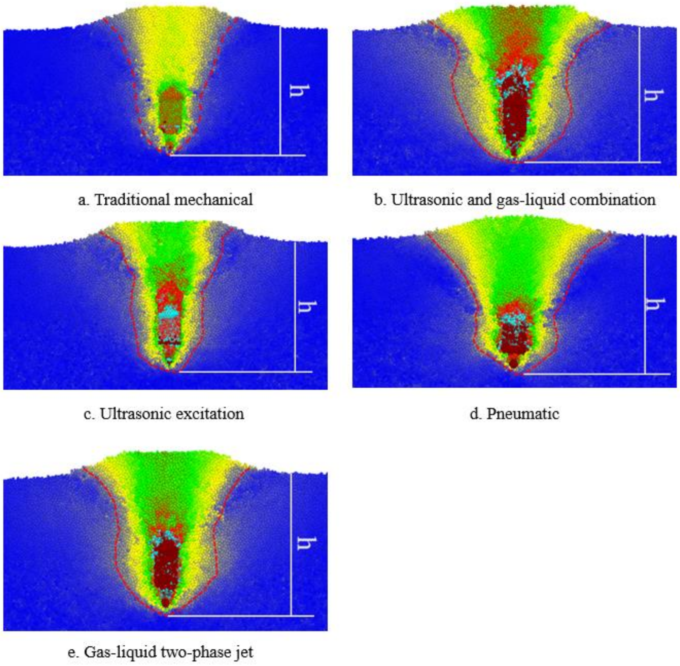
(b) Field experiment on soil tillage resistance

Fig. 4 - Tillage resistance diagram

The resistance of ultrasonic-excited gas-liquid two-phase jet is significantly reduced, because high-pressure water and air are thoroughly mixed in the mixer to form a uniform gas-liquid two-phase jet, which has high speed and impact force when ejected. Through the gas-liquid two-phase jet splitting effect, micro-cracks are pre-created in the compact soil, weakening the soil strength and achieving the effect of drag reduction during the subsoiling process. The ultrasonic generator causes the subsoiling shovel to produce high-frequency and low-amplitude vibrations. These vibrations are transmitted into the soil in the form of stress waves, forcing the soil particles to vibrate. This instantly destroys the cohesion and internal friction structure among them, significantly reducing the soil's shear strength and making it easier to loosen. The combination of ultrasonic excitation and gas-liquid two-phase jet can significantly reduce the tillage resistance during subsoiling operations and lower energy consumption.

The influence of different subsoiling methods on the area of soil disturbance

The soil disturbance profiles resulting from different subsoiling methods were compared through simulation experiments, as shown in Fig. 5a-e. In the figure, different particle colors represent varying degrees of soil disturbance, with darker colors indicating more intense disturbance. Notably, the color deepens with proximity to the subsoiler's working path. A comparison of the different methods reveals that the ultrasonic vibration-assisted gas-liquid two-phase jet subsoiling produced the darkest coloration and the largest disturbed area, measuring 62,104.8 mm². This was followed by gas-liquid two-phase jet subsoiling alone (59,437.2 mm²), pneumatic subsoiling (57,910.4 mm²), and ultrasonic vibration subsoiling alone (54,837.9 mm²). Traditional mechanical subsoiling exhibited the lightest coloration and the smallest disturbed area, at 51,859.6 mm². Although the disturbed area of ultrasonic vibration subsoiling was comparable to that of traditional mechanical subsoiling, its darker color indicates a higher degree of soil disturbance. These results demonstrate that the ultrasonic vibration-assisted gas-liquid two-phase jet subsoiling achieved the most extensive soil disturbance, as evidenced by the largest disturbed area and the most intense particle displacement, thereby confirming its superior subsoiling performance.



a. Traditional mechanical
b. Ultrasonic and gas-liquid combination
c. Ultrasonic excitation
d. Pneumatic
e. Gas-liquid two-phase jet

Fig. 5 - Simulated soil disturbance profile

The soil disturbance areas of different subsoiling methods were compared through field experiments as shown in Fig. 6. The maximum soil disturbance area of ultrasonic-excited gas-liquid two-phase jet subsoiling is 60009.4 mm², followed by gas-liquid two-phase jet subsoiling with a soil disturbance area of 55,750.2 mm², and pneumatic subsoiling with a soil disturbance area of 55,206.4 mm². The soil disturbance area of subsoiling by ultrasonic excitation is 54,229.4 mm², and the minimum is that of traditional mechanical subsoiling, with a soil disturbance area of 52,446.1 mm². The soil disturbance area of subsoiling by ultrasonic excitation gas-liquid two-phase jet is 7,563.6 mm² larger than that of traditional mechanical subsoiling. The difference in soil disturbance area between gas-liquid two-phase jet subsoiling and pneumatic subsoiling is relatively small, only 548.3 mm². Consistent with the results of the simulation experiment, the subsoiling soil disturbance area of the ultrasonic-excited gas-liquid two-phase jet is the largest. This means that the subsoiling method of the ultrasonic-excited gas-liquid two-phase jet has a greater impact on the physical structure of the soil, which can break the hard plough layer and create rich soil pores.

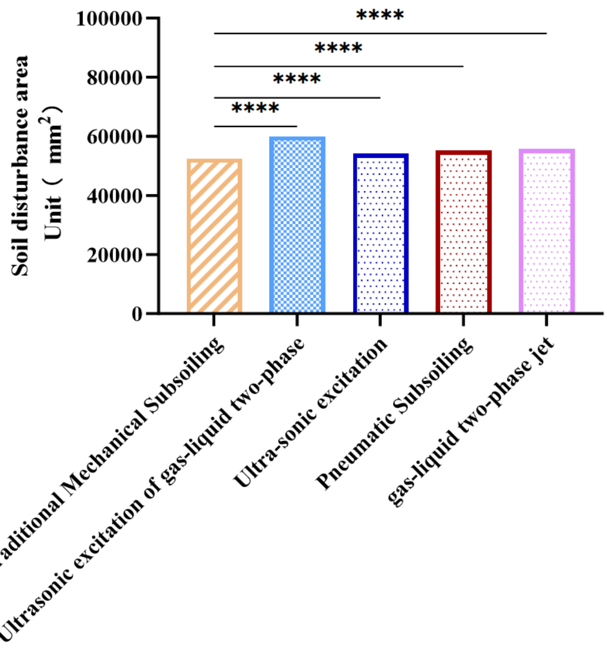


Fig. 6 - Soil disturbance in the field test

The combination of ultrasonic excitation and gas-liquid two-phase jet has a good subsoiling effect because ultrasonic waves, through high-frequency force application, cause uniform vibration of soil particles, thereby forming a wider disturbance area on the soil profile. The high-frequency vibration waves of ultrasonic waves are conducted to deeper soil layers, further loosening the deep soil, expanding the disturbance area in the vertical direction, and enhancing the deep loosening effect. After the gas-liquid two-phase jet comes into contact with the soil, it generates high-speed impact, which can cut and strip the soil, forming a larger disturbance area than traditional mechanical subsoiling. The turbulent effect generated by the gas-liquid two-phase jet can create intense lateral and longitudinal impacts in the soil, causing diffused disturbances to the surrounding soil. The high kinetic energy of the gas-liquid two-phase jet penetrates deeper into the soil layer, exerting disturbance and loosening effects on the deep soil, thereby increasing the horizontal and vertical range of soil disturbance. The subsoiling effect has been significantly enhanced by combining ultrasonic excitation with gas-liquid two-phase jet flow.

The influence of different subsoiling methods on soil porosity

The effects of different subsoiling methods on soil porosity were validated through soil bin experiments, as shown in Fig. 7. Overall, the porosity variations under each treatment exhibited a spatial distribution pattern characterized by an initial increase followed by a gradual decrease with increasing depth. The most pronounced changes in porosity were concentrated in the 12-20 cm soil layer, whereas porosity remained relatively low both below 30 cm and within the uppermost 10-12 cm layer. In the absence of subsoiling treatment, the soil porosity was uniformly low throughout the profile, serving as a benchmark for evaluating the improvement effects of the various subsoiling methods.

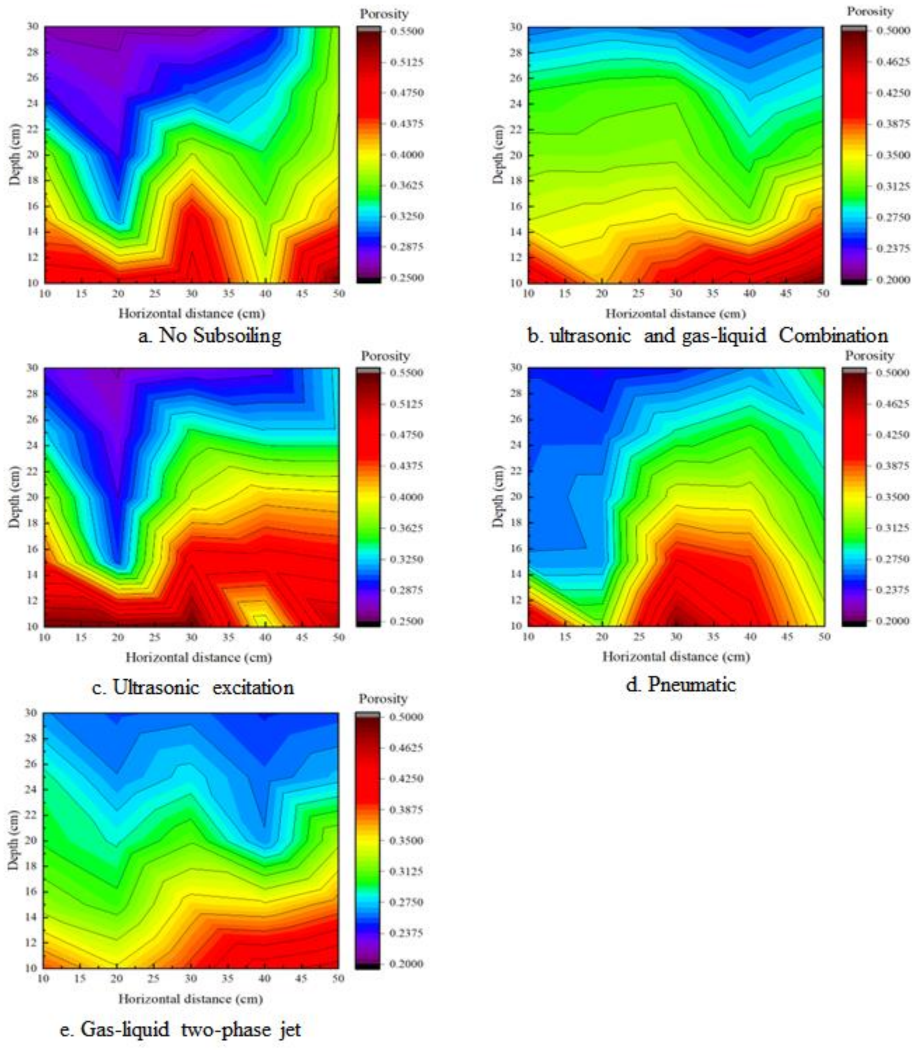


Fig. 7 - Soil porosity contour map

From the perspective of both the degree of improvement and the uniformity of porosity distribution, the different subsoiling methods exhibit notable differences in their effectiveness. Among these, the combination of ultrasonic excitation and gas-liquid two-phase jet subsoiling yields the broadest distribution within the high porosity region (0.31-0.50) and demonstrates the best continuity. Within the 12-26 cm depth range, porosity remains consistently high, while the horizontal disturbance extends across 20-50 cm. The uniformity of soil loosening achieved by this combined method is significantly superior to that of other treatments, highlighting the synergistic effect of excitation and jet action. Gas-liquid two-phase jet deep loosening alone also results in a wide distribution in the high porosity region, with porosity values ranging from 0.31 to 0.46 within the 12-24 cm soil layer. Its horizontal disturbance range is similar to that of the combined treatment; however, porosity below 24 cm decreases at a slightly faster rate. In contrast, pneumatic subsoiling concentrates the high porosity zone primarily within the 12-20 cm layer, with a horizontal disturbance range of approximately 20-45 cm. Below 20 cm, the increase in porosity is limited, and the depth of improvement is somewhat shallower than that of the gas-liquid two-phase jet treatment. Ultrasonic excitation subsoiling alone exhibits a high porosity region concentrated between 12 and 18 cm, with a V-shaped disturbance pattern in the horizontal direction. The porosity increase in deeper layers (below 20 cm) is limited; however, this method results in notably higher porosity in the surface layer (10-12 cm) compared to other single-treatment approaches.

The combination of ultrasonic excitation and gas-liquid two-phase jetting proves most effective at improving subsoil porosity through deep tillage. The underlying mechanism is that high-frequency ultrasonic vibration effectively breaks down soil aggregates and reduces cohesion, while the gas-liquid two-phase jet expands pore spaces and facilitates water and gas movement via high-speed fluid impact. The synergy between these two actions thus achieves a superior deep tillage outcome. In contrast, single-method deep tillage approaches are constrained by their respective mechanisms, resulting in limitations in either improvement depth or range. Specifically, gas–liquid two-phase jetting and pneumatic deep tillage depend on fluid impact but lack sufficient capability for deep soil fragmentation. Meanwhile, ultrasonic excitation alone experiences rapid energy attenuation in the soil and can only generate effective disturbance within shallow layers.

CONCLUSIONS

An ultrasonic vibration-assisted gas-liquid two-phase jet subsoiling machine was designed, and comparative investigations were carried out through simulation tests, soil bin tests, and field experiments to evaluate the performance of combined ultrasonic vibration and gas-liquid two-phase jet subsoiling, gas-liquid two-phase jet subsoiling, ultrasonic vibration subsoiling, pneumatic subsoiling, and traditional mechanical subsoiling in terms of tillage resistance, soil disturbance area, and soil porosity. The main conclusions are as follows:

(1) Both simulation and field experiments were conducted to validate the tillage resistance and soil disturbance area of different subsoiling methods. The experimental results from simulations and field tests were consistent, demonstrating that the combined ultrasonic vibration and gas-liquid two-phase jet subsoiling method achieved the smallest tillage resistance and the largest soil disturbance area. Compared with traditional mechanical subsoiling, the combined method reduced tillage resistance by 17.5% and increased the soil disturbance area by 14.4%.

(2) Soil bin tests were conducted to evaluate changes in the soil disturbance area under different subsoiling methods. The results demonstrated that the combined ultrasonic vibration and gas-liquid two-phase jet subsoiling exhibited the most significant change in soil porosity, with an increase of 0.1150 mm compared to the non-loosened condition. Comprehensive analysis confirmed that the combined ultrasonic vibration and gas-liquid two-phase jet subsoiling method achieved the lowest tillage resistance and provided the most effective subsoiling performance.

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REFERENCES

[1] Ahmadi, I. (2017). Effect of soil, machine, and working state parameters on the required draft force of a subsoiler using a theoretical draft-calculating model. *Soil Research*, 55(4), 389. https://doi.org/10.1071/SR16193

[2] Baars, S. V. (2008). Advanced Soil Mechanics. *TAYLOR & FRANCIS*. https://doi.org/doi:http://dx.doi.org/

[3] Babaiwa, D. A., & Ikponmwen, M. O. (2021). Application of 2D and 3D Electrical Resistivity Tomography (ERT) in Predicting Soil Erodibility in Oredide Village, Auchi in Etsako West LGA of Edo State, Southern Nigeria. *Journal of Applied Sciences & Environmental Management*, 25(6), 887-891. https://doi.org/10.4314/jasem.v25i6.28

[4] Cheng, J., Zheng, K., Xia, J., Zhang, B., Ni, Y., & Ma, J. (2025). Effects of ultrasonic vibration-assisted cutting on tillage blade performance and soil fragmentation characteristics under different soil moisture contents. *Soil and Tillage Research*, 252, 106575. https://doi.org/10.1016/j.still.2025.106575

[5] Li, X., Wang, S., Meng, H., Qu, Q., & Jia, Y. (2022). Research on drag reduction mechanism of pneumatic subsoiler and establishment of resistance mathematical model. *Canadian Journal of Soil Science*, 102(2), 531-548. Scopus. https://doi.org/10.1139/cjss-2021-0101

[6] Liu, Q., Huang, Q., Wang, G., Xie, S., & Wang, E. (2023). Experimental study on the effects of ultrasonic excitation on pore structure of water-bearing coal. *International Journal of Rock Mechanics and Mining Sciences*, 170, 105548. https://doi.org/10.1016/j.ijrmms.2023.105548

[7] Mahalleh, H. A. M., Siavoshnia, M., & Yazdi, M. (2021). Effects of electro-osmosis on the properties of high plasticity clay soil: Chemical and geotechnical investigations. *Journal of Electroanalytical Chemistry*, 880, 114890. https://doi.org/10.1016/j.jelechem.2020.114890

[8] Martínez, I. G., Prat, C., Ovalle, C., del Pozo, A., Stolpe, N., & Zagal, E. (2012). Subsoiling improves conservation tillage in cereal production of severely degraded Alfisols under Mediterranean climate. *Geoderma*, 189-190, 10-17. https://doi.org/10.1016/j.geoderma.2012.03.025

[9] Pan, B., A, R., Guo, Y., Zhang, L., Wei, B., & Zhou, W. (2021). Study on the relationship between complex resistivity and water saturation in fractured rock at low frequency. *Acta Geophysica Sinica*, 64(10), 3774-3787. Scopus. https://doi.org/10.6038/cjg2021O0084

[10] Ren, L., Cornelis, W. M., Ruysschaert, G., De Pue, J., Lootens, P., & D'Hose, T. (2022). Quantifying the impact of induced topsoil and historical subsoil compaction as well as the persistence of subsoiling. *Geoderma*, 424, 116024. https://doi.org/10.1016/j.geoderma.2022.116024

[11] Sanchez, C., Arribart, H., & Giraud Guille, M. M. (2005). Biomimetism and bioinspiration as tools for the design of innovative materials and systems. *Nature Materials*, 4(4), 277-288. https://doi.org/10.1038/nmat1339

[12] Shah, A. N., Tanveer, M., Shahzad, B., Yang, G., Fahad, S., Ali, S., Bukhari, M. A., Tung, S. A., Hafeez, A., & Souliyanonh, B. (2017). Soil compaction effects on soil health and crop productivity: An overview. *Environmental Science and Pollution Research*, 24(11), 10056-10067. https://doi.org/10.1007/s11356-017-8421-y

[13] Shi, F., Zhao, J., Zhou, Y., & Zhang, H. (2023). Experiments and simulations of surface cleaning for a gas-liquid two-phase jet. *Water Science and Technology*, 87(3), 748-760. https://doi.org/10.2166/wst.2023.029

[14] Sun, J., Wang, Y., Ma, Y., Tong, J., & Zhang, Z. (2018). DEM simulation of bionic subsoilers (tillage depth >40 cm) with drag reduction and lower soil disturbance characteristics. *Advances in Engineering Software*, 119, 30-37. https://doi.org/10.1016/j.advengsoft.2018.02.001

[15] Tracy, S. R., Black, C. R., Roberts, J. A., & Mooney, S. J. (2011). Soil compaction: A review of past and present techniques for investigating effects on root growth: Effect of soil compaction on root growth. *Journal of the Science of Food and Agriculture*, 91(9), 1528-1537. https://doi.org/10.1002/jsfa.4424

[16] Wang, J., Wang, D., & Zhao, Z. (2021). Mechanical properties of soil-engaging components interacted with ultrasonic vibration in agricultural machinery. *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering*, 37(23), 35-41. https://doi.org/10.11975/j.issn.1002-6819.2021.23.005

[17] Wang, Y., Li, N., Ma, Y., Tong, J., Pfleging, W., & Sun, J. (2020). Field experiments evaluating a biomimetic shark-inspired (BioS) subsoiler for tillage resistance reduction. *Soil and Tillage Research*, 196, 104432. https://doi.org/10.1016/j.still.2019.104432

[18] Wang, Y., N Osman, A., Zhang, D., Yang, L., Cui, T., Zhong, X., 1. College of Engineering, China Agricultural University, Beijing 100083, China, & 2. Department of Agricultural Machinery, College of Agricultural Studies, Sudan University of Science and Technology, Khartoum, Sudan. (2019). Optimized design and field experiment of a staggered vibrating subsoiler for conservation tillage. *International Journal of Agricultural and Biological Engineering*, 12(1), 59-65. https://doi.org/10.25165/j.ijabe.20191201.4297

[19] Zhao, J., Lu, Y., Wang, X., Zhuang, J., & Han, Z. (2023). A bionic profiling-energy storage device based on MBD-DEM coupled simulation optimization reducing the energy consumption of deep loosening. *Soil and Tillage Research*, 234, 105824. https://doi.org/10.1016/j.still.2023.105824

[20] Zheng, K., He, J., Li, H., Diao, P., & Zhao, H. (2016). Research on polyline soil-breaking blade subsoiler based on subsoiling soil model using discrete element method. *Transactions of the Chinese Society for Agricultural Machinery,* 47 (09): 62-72. https://doi.org/10.6041/j.issn.1000-1298.2016.09.010

[21] Zuo, S., Kong, D., Liu, L., Dong, X., & Zhao, Y. (2016). Experiment on effect of air-pressure subsoiling based on air-pressure cracking theory. *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering*, 32(1), 54-61. https://doi.org/10.11975/j.issn.1002-6819.2016.01.007