Mechanical characteristic analysis of rice seedlings under water wave stress

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Abstract: Machine transplanting as an advanced technology in rice cultivation has been widely adopted. Nevertheless, under extreme wind conditions, transplanted rice seedlings can float and then die off due to external forces generated by wind and water waves. Studying the mechanical characteristics of these seedlings is essential for understanding the underlying mechanisms of rice seedling floating. In this study, the Volume of Fluid (VOF) method is applied to study the flow mechanisms of water waves around rice seedlings. It is found that the pressure differential between the windward and leeward wave sides of the rice seedlings changes during wave diffraction, resulting in unsteady drag forces. The drag force reaches its maximum value when the wave crest propagates to the rice seedlings. Under the condition where waves do not break, increasing wave height does not alter the fluctuation pattern of drag force but leads to a larger drag force amplitude. When the wave height increases sufficiently to cause wave breaking, additional loads are generated, resulting in a significant increase in drag amplitude and exciting new high-frequency disturbances. Increasing wavelength reduces the drag force amplitude but raises its fundamental fluctuation frequency and introduces new low-frequency pulsations. As the rice seedlings tilt, the altered flow mechanism has an uncertain effect on the variation in drag force amplitude and generates new excitations with other frequencies. It indicates that increased wave height, decreased wavelength, and rice seedling inclination may all elevate the risk of rice seedlings lodging. These results could provide valuable references for the prevention of floating rice seedlings.

Keywords: agricultural engineering, floating rice seedlings, water wave stress, computational fluid dynamics, Volume of Fluid
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1 Introduction

Rice as a unique crop among major grain crops has strong adaptability to edaphic and climatic conditions[1]. It occupies an important position in the world's agricultural production[2,3]. Rice production is of great significance to ensuring global food security. In recent years, the rapid development of agricultural technology has promoted the transformation of rice production modes[4-7]. Machine transplanting as an advanced rice transplanting method has been introduced to rice cultivation, where it not only improves labor productivity but also reduces manpower costs and labor intensity[8-11]. However, transplanted rice seedlings have a poor root system and may fail to root firmly in the soil at the initial stage after transplantation. Once encountering extreme weather conditions, they float on the water surface and may eventually fail to grow normally or even die due to external factors such as wind and water waves[12].

Recently, ensuring stable production of staple food crops, particularly rice, has become increasingly challenging due to the heightened intensity and frequency of extreme weather events resulting from global climate change[1,13]. Floating rice seedlings, as an important constraining factor limiting rice production, are influenced by many elements, such as ground roughness, rice seedling throwing equipment, and external force stress (wind and water wave). Significant research efforts have been devoted to optimizing rice transplanting techniques in recent years, aiming to enhance seedling establishment success rates. Novel transplanting mechanisms and innovative transplanter designs have to some extent demonstrated significantly improved operational performance, achieving satisfactory outcomes in terms of transplanting accuracy and efficiency[14-16]. However, these methods are largely based on experience, lack systematic theoretical support, and face a number of limitations in practice. Therefore, there is an urgent need to analyze the dynamic response of rice seedlings under the stress of external force, and to clarify the affecting mechanism and factors of external force stress on rice seedlings.

The rice transplanting period often coincides with periods of frequent strong winds. On the one hand, wind forces act directly on rice seedlings and generate the drag force; on the other hand, they induce water waves to strike rice seedlings and affect their floating. Experimental measurement of dynamic force on rice seedlings is difficult due to their small size. The rapid development of CFD (computational fluid dynamics) methods in recent years has provided new opportunities to address this challenge. Free from experimental site and equipment size constraints, this approach enables comprehensive flow field data acquisition and clear visualization of complex flow phenomena, which are essential for studying flow mechanisms. It is widely used in aerospace, automotive, and chemical engineering for its well-established

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accuracy[17,18]. This technology has also been gradually introduced into agricultural research in recent years. Hu et al.[19] analyzed the kinematic response of rice under a near-ground wind field, while Ni et al.[20] studied rice lodging in farmland wind fields using a simplified rice model based on CFD. However, existing studies have primarily focused on the mechanical characteristics of mature rice seedlings or other plants under wind stress, while the effect of water wave force stress on rice seedlings has received little attention. Consequently, there is no systematic understanding of the mechanisms underlying water wave stress, particularly during the rice transplanting period. To address this gap, this study employs CFD to analyze the mechanical characteristics of rice seedlings under water wave stress.

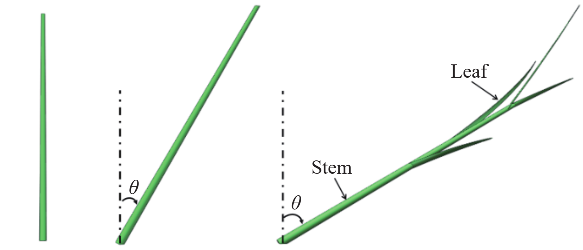
This paper is organized as follows. Firstly, the numerical method for the water wave drag force on rice seedlings is presented and validated by experimental data. Secondly, the governing mechanisms of wave-induced rice seedling floating are elucidated, with a focus on the effects of wave height, wavelength, and rice seedling posture. Finally, the key findings and conclusions are summarized.

2 Model and numerical method

The studied paddy fields are situated in northeast China's Heilongjiang Province. At transplanting, rice seedlings typically stand 12-20 cm tall with a flat, sturdy stem base. Key morphological features include a mesocotyl length under 3 mm, a first leaf sheath height below 3 cm, an auricle distance of approximately 1 cm, and progressively increasing leaf lengths. The rice seedlings feature 3-5 wide and thick leaves, demonstrating a gradient growth pattern: the first leaf measures approximately 2 cm in length, the second 5 cm, and subsequent leaves 8 cm. Their stem bases are flat and broad (2-4 mm in diameter), with short mesocotyls and no signs of excessive elongation.

To build a geometric model of rice for this research, a sample of 100 rice seedlings was collected during the transplanting period to obtain their morphological data. Considering the inclination changes of rice seedlings under the water wave stress, three inclined angles (0°, 30°, and 60°) are selected to study the effect of rice posture on drag force characteristics (see Figure 1). It should be emphasized that the inclined angle θ is defined as the clockwise angle deviation from the vertical direction, as illustrated in Figure 1. In this study, the initial height of the water free surface was set to 4 cm, and the maximum wave height (the vertical distance between wave crest and wave trough) reached 3.5 cm. Consequently, the maximum vertical distance over which the water wave could exert an effect was 5.75 cm. The vertical distance from the root to the lowest leaf of the rice seedling was 7.3 cm. Therefore, the water wave could not reach the leaves of rice seedlings with small inclination angles (θ=0°, 30°). To simplify the rice seedling model and reduce computational cost, the leaves were omitted in the simulations. When the inclined angle θ reaches 60°, the influence of water wave force on leaves of rice seedlings should be considered. As a result, the simplified rice seedling model consists of one stem and four leaves in this case (see Figure 1c.). To further simplify the calculation, the rice seedling is assumed to act as a rigid body under the wave force, and its deformation is ignored.

Figure 2 shows the sketch of the computational domain of this flow. It is a cuboid with dimensions of 1274 mm (length), 204 mm (width), and 212 mm (height). An unstructured polyhedral mesh system is applied to discretize the computational domain, as shown in Figure 3. The regions around the rice seedlings and those near the water surface are refined to capture the fine flow structures. The growth rate of the volume mesh in the refined regions is 1.25, the minimum mesh size is 0.04 mm, and the maximum mesh size is less than 5 mm. The number of boundary layers is adjusted from 10 to 15 based on the geometry, and the total number of mesh elements is approximately 11 million.



a. θ=0° b. θ=30° c. θ=60°

Figure 1 Models of the rice seedling at different inclined angles

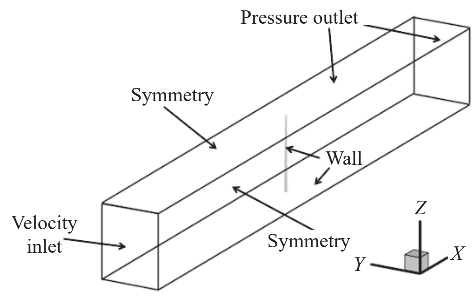


Figure 2 Sketch of the computational domain

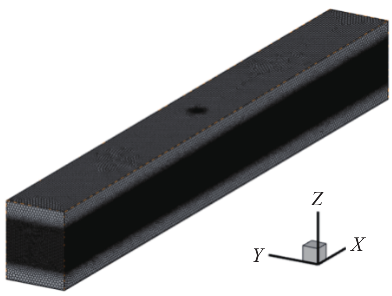


Figure 3 Grid distribution of the overall calculation domain

The flow around rice seedlings is characterized by incompressibility and viscosity and is governed by the continuity equation (see Equation (1)) and the momentum equation (the Navier-Stokes equation; see Equation (2)).

$$\frac{\partial \rho u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \rho g \tag{2}$$

where, u_i is the velocity of a fluid particle in i direction, m/s; the subscript i=1, 2, 3 implies x, y, and z directions respectively; t is the time, s; p is the pressure, Pa; ρ is the fluid density, kg/m^3; μ is the fluid viscosity coefficient, kg/m·s; and g is the gravitational acceleration, m/s^2.

The Volume of Fluid (VOF) method is used to capture the free surfaces in the numerical model. The α as the volume fraction for each calculation unit is introduced, and it is expressed as:

$$\alpha = \begin{cases} 0, & \text{gaseous phase} \\ 0-1, & \text{free surface} \\ 1, & \text{liquid phase} \end{cases} \tag{3}$$

The calculation formulas for the density and viscosity coefficient of the mixed fluid are as follows:

$$\rho = \alpha\rho_w + (1-\alpha)\rho_g \tag{4}$$

$$\mu = \alpha\mu_w + (1-\alpha)\mu_g \tag{5}$$

where, the subscripts w and g represent the liquid phase and the gaseous phase, respectively.

The unsteady incompressible Navier-Stokes equations and the continuity equation are discretized using the finite-volume method. A velocity inlet condition is imposed at the inlet boundary, meaning that waves are generated using the velocity boundary method. The top and outlet boundaries are set as pressure outlets. The bottom boundary and the surfaces of the rice seedlings are treated as adiabatic with no-slip conditions, while all other boundaries are designated as symmetry boundaries. The wave generation zone is positioned at the upstream end of the computational domain, where it actively generates target waves while attenuating reflected waves. Concurrently, a damping absorption zone is implemented at the downstream end to eliminate wave reflections at the outlet boundary through viscous dissipation mechanisms. The SIMPLEC algorithm is employed to decouple pressure and velocity, and the second-order upwind scheme is adopted for spatial discretization. Because the flow around the rice seedlings is laminar, the laminar flow model is used in the solution process.

The small size of rice seedlings precludes direct experimental measurement or indirect force characterization using experimental models. The flow of water waves around rice seedlings is similar to that around a cylinder. To validate the accuracy and reliability of the numerical methodology proposed in this study, a benchmark case of flow around a cylinder under analogous conditions is employed. Figure 4 compares the wave force on the cylinder obtained from CFD results and experimental data[21]. It shows that the dimensionless wave force F' from the CFD is in agreement with the experiment, where $F' = F/(\rho g D H^2)$, $t' = t/T$, F is the wave force, ρ is the density of water, g is the gravitational acceleration, D=0.7 m is the cylinder diameter, H=1.2 m is wave height, and T= 4 s is the wave period. This indicates that the numerical method applied in this paper is reliable and can provide high-precision calculation results for the later sections.

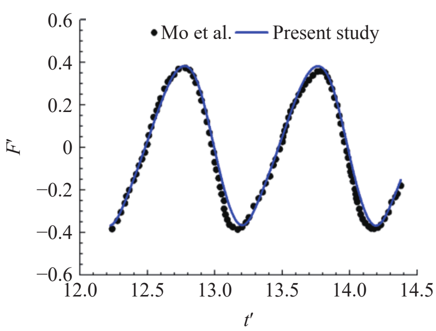


Figure 4 Comparison of wave force obtained from CFD results and the experiment data

3 Results and discussion

During strong wind conditions, the water waves in paddy fields exhibit complex spatiotemporal variation characteristics, while rice seedlings demonstrate intricate dynamic response patterns in their postures under water wave forces. The wave force on rice seedlings under water stress is mainly affected by wave height, wavelength, and the posture of the rice seedlings. Hence, combined with the meteorological data from rice-producing areas, the influence of the above factors on the mechanical characteristics of rice seedlings was studied.

3.1 Effect of wave height on drag force characteristics

The rice seedling transplanting period in Heilongjiang Province primarily occurs from mid to late May, with average wind forces reaching levels 4-6 (5.0-14.0 m/s). Under extreme weather conditions, the wind not only imposes direct forces on rice seedlings but also generates propagating waves. These waves exert cyclic hydrodynamic loading on the seedlings, directly compromising the anchoring strength between the root systems and the soil, thereby escalating the risk of rice seedling floating. The waves in paddy fields belong to shallow-water waves induced by wind, which have complex nonlinear dynamic characteristics. It was found through experimental measurements that the water waves exhibit a typical height H ranging in 2-4 cm and a wavelength λ spanning 20-40 cm. Based on these data, wave heights of 1.5 cm, 2.5 cm, 3.0 cm, and 3.5 cm were adopted to analyze their effects on the dynamic characteristics of rice seedlings at a fixed wavelength (λ = 35 cm).

The water wave forces mainly include lift force, drag force, and the moment of the drag force. Under the same conditions (using the example of H = 1.5 cm, λ = 35 cm), the peak lift force (0.0006 N) induced by water waves is far smaller than the soil anchoring force (0.13-0.32 N)[22] and acts in the same direction, so it has no effect on the floating rice seedlings. Moreover, the peak moment of the drag force (0.000 08 N·m) is lower than that under wind loading (0.001-0.006 N·m)[22]. Therefore, its influence can be neglected. The drag force refers to the resistance generated when a water wave acts on the surface of rice seedling stems, and this force acts in the horizontal direction. The drag force is an important parameter for evaluating the effect of wind stress on rice seedling lodging and floating. Therefore, only the drag force is presented in the later section.

Figure 5 illustrates the drag force amplitude of rice seedlings under different wave heights. It shows that the drag force amplitude A increases with wave height H increasing. It should be emphasized that the growth rate of drag force amplitude increases significantly after the wave height reaches 3.0 cm. The drag force amplitude is about 0.025 N at H = 3.5 cm.

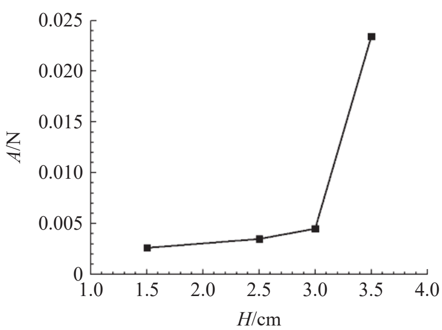
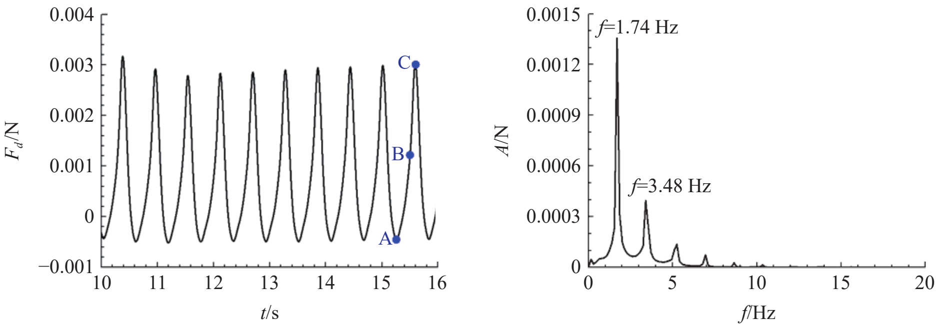


Figure 5 Drag force amplitude of the rice seedling under different wave heights for λ=35 cm

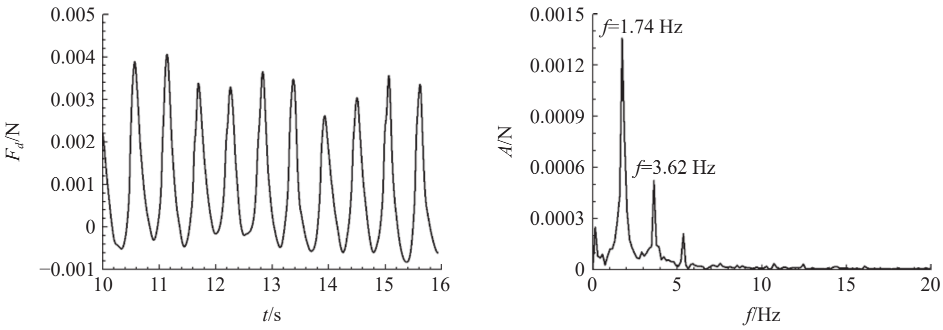
To further investigate the influence of wave height on the drag force characteristics of rice seedlings under water wave stress, three wave height conditions (1.5 cm, 2.5 cm, and 3.5 cm) were selected for force analysis on the rice seedlings. As the wave loads represent an unsteady process, a Fast Fourier Transform (FFT) was applied to analyze the pulsating characteristics of the drag force on rice seedlings.

Figures 6-8 show the time-varying drag force F_d curves and their FFT results under the three wave heights. As shown in the figures, the drag force on rice seedlings exhibits periodic variations over time under different wave heights. With increasing wave height, the inhomogeneity of the drag force amplitude fluctuations intensifies. Furthermore, the drag force amplitude progressively increases, showing a significant surge, particularly when the wave height reaches 3.5 cm. The FFT results show that the fluctuation frequency of the drag force under various wave heights is 1.74 Hz and its harmonic frequencies. As wave height increases, the amplitude of the fundamental frequency gradually rises, aligning with the trend of drag force amplitude variation. Meanwhile, higher-frequency disturbances at twice the fundamental frequency and above are markedly enhanced, which indicates intensified unsteady effects of wave forces on rice seedlings. These results demonstrate that wave height significantly influences the phenomenon of rice seedling floating. The above results indicate that increased wave height not only amplifies drag force intensity but also complicates the frequency characteristics of waves, leading to more complex dynamic behaviors.



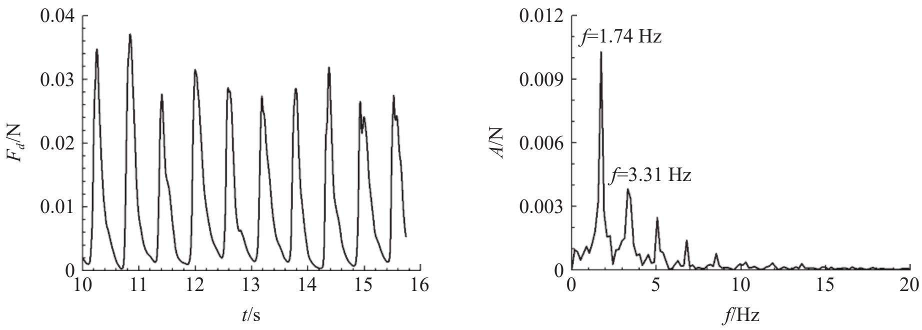
a. Drag force curve b. FFT results

Figure 6 Time-varying drag force curve and its FFT result for H=1.5 cm and λ=35 cm



a. Drag force curve b. FFT results

Figure 7 Time-varying drag force curve and its FFT result for H=2.5 cm and λ=35 cm



a. Drag force curve b. FFT results

Figure 8 Time-varying drag force curve and its FFT result for H=3.5 cm and λ=35 cm

To analyze the unsteady fluctuation mechanism of the drag force, the trough, median, and peak points of the drag force curve in one cycle are selected to study, corresponding to points A (t=15.26 s), B (t=15.50 s), and C (t=15.60 s) in Figure 6a. The water volume fraction contours in streamwise symmetry plane and surface pressure contours of rice seedlings for H=1.5 cm are shown in Figures 9-11. As illustrated in Figure 9, when the rice seedling is located between two wave crests, the pressure difference generated by the water wave on its windward and leeward wave sides is relatively small, resulting in a small drag force. The disparity in pressure distribution between the windward and leeward wave sides varies as the water wave crest moves. As the wave crest approaches the rice seedling, the pressure on the windward wave side increases progressively, which induces a greater pressure difference between the windward and leeward wave sides, thereby generating a greater drag force (see Figure 10). When the wave crest reaches the rice seedling, it results in the maximum pressure difference, leading to the peak drag force. Consequently, the periodic fluctuation of water waves exerts a cyclic drag force on the rice seedlings, causing loosening of the root system of rice seedlings. It in turn leads to a weakened soil anchoring force of the rice seedlings, resulting in the phenomenon of floating rice seedlings.

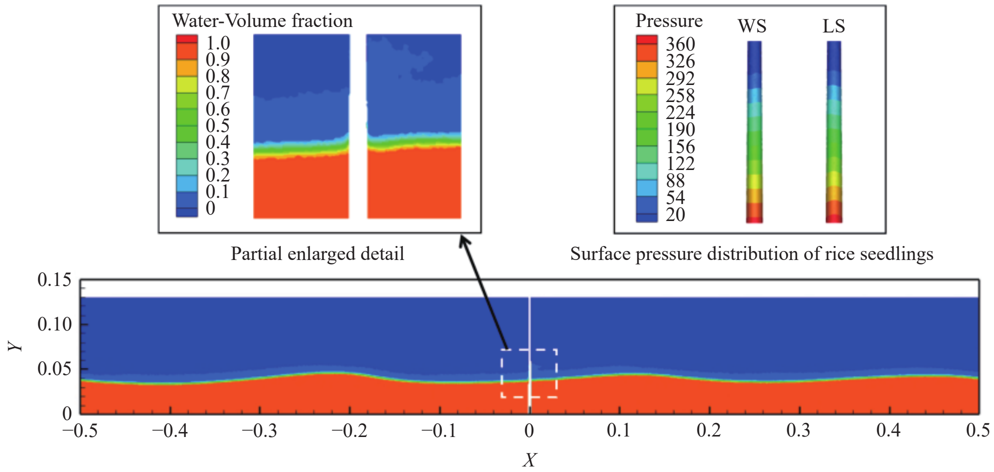


Figure 9 Water volume fraction contour and surface pressure contour of rice seedling at the trough point of drag force curve for H=1.5 cm and λ=35 cm (t=15.26 s)

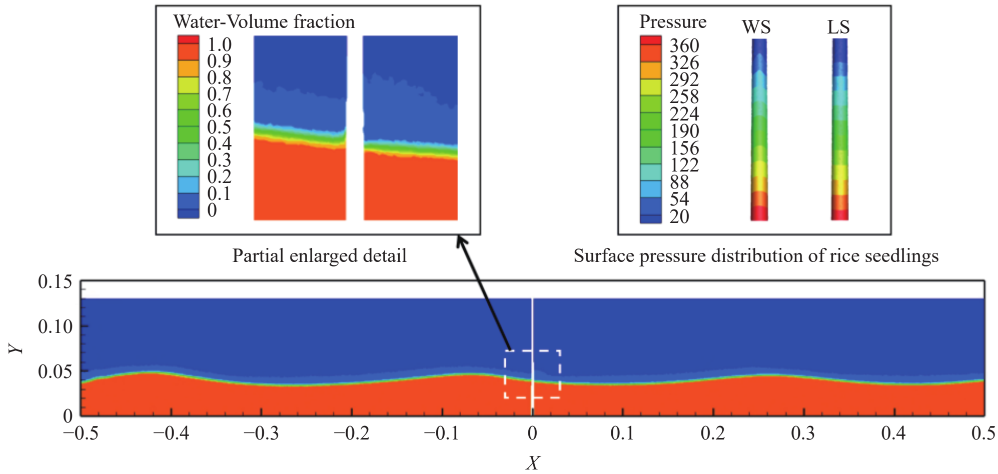


Figure 10 Water volume fraction contour and surface pressure contour of rice seedling at the median value point of drag force curve for H=1.5 cm and λ=35 cm (t=15.50 s)

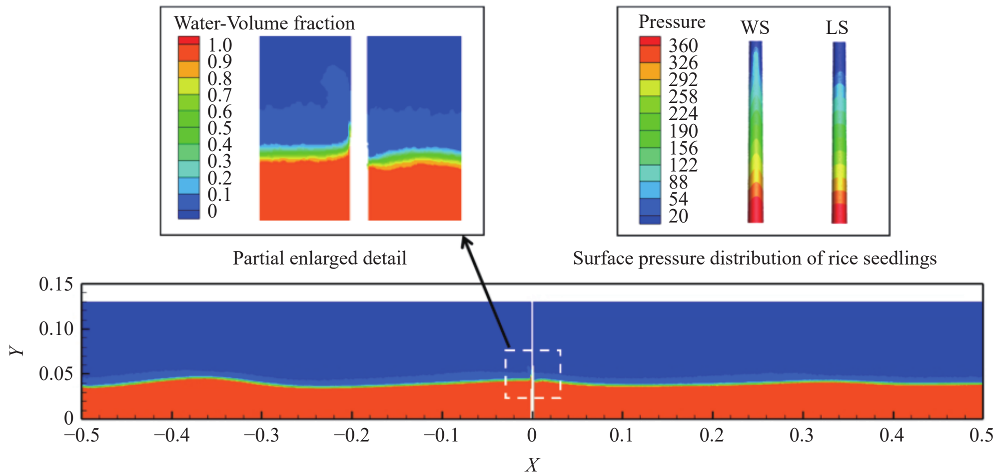


Figure 11 Water volume fraction contour and surface pressure contour of rice seedling at the peak point of drag force curve for H=1.5 cm and λ=35 cm (t=15.60 s)

To further investigate how wave height influences the drag force on rice seedlings, we compared the water volume fraction and surface pressure contours at the peak point of the drag force curve. The analysis focuses on wave heights of 2.5 cm and 3.5 cm, using the 1.5 cm condition as a benchmark. As presented in Figures 12 and 13, when the wave height increases to 2.5 cm, wave breaking is not observed. In this regime, the interaction mechanism of water waves with rice seedlings is similar to that under the 1.5 cm wave height. The primary effect of the increased wave height is a larger force-exerting area on the rice seedling, consequently leading to an increase in the amplitude of the observed drag force.

However, when the wave height is further increased to 3.5 cm, wave breaking occurs. The impact of the broken wave on the seedlings generates an additional impulsive load. This impact significantly increases the pressure differential force between the windward and leeward wave sides of the rice seedling, resulting in a substantially larger drag force. Furthermore, in addition to the periodic excitation from the wave force, the rice seedlings are also subjected to unsteady loading induced by the breaking wave. This combination enhances the fluctuating nature of the drag force (manifested as excitation across a broader frequency spectrum in Figure 8b). Such pulsating characteristics have the potential to induce increased oscillation of the seedlings. This oscillation could in turn lead to a reduction in the soil anchoring force provided by the roots of the rice seedlings, thereby increasing the risk of rice seedlings floating.

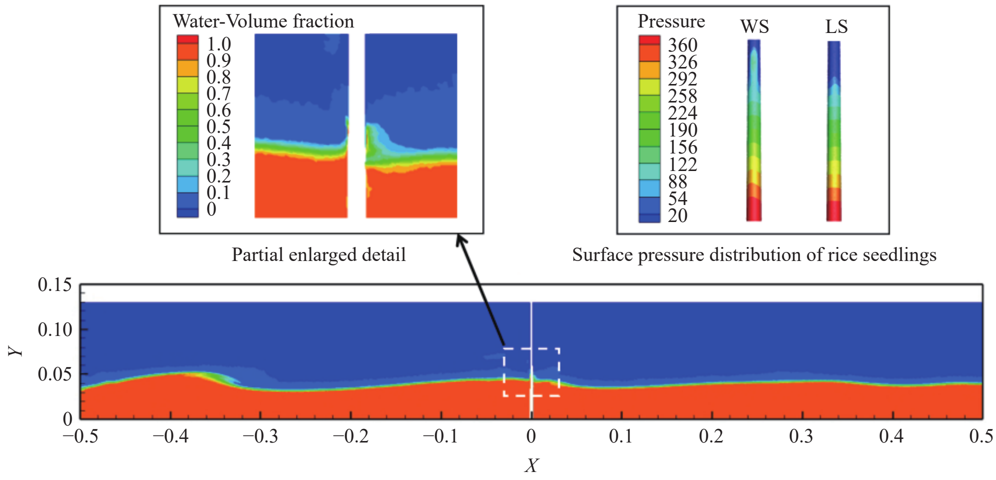


Figure 12 Water volume fraction contour and surface pressure contour of rice seedling at the peak point of drag force curve for H=2.5 cm and λ=35 cm (t=15.06 s)

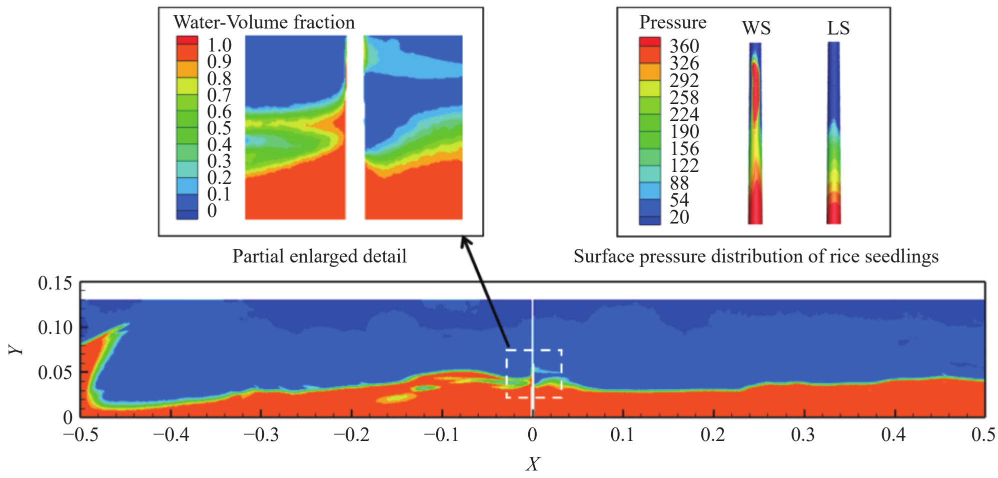


Figure 13 Water volume fraction contour and surface pressure contour of rice seedling at the peak point of drag force curve for H=3.5 cm and λ=35 cm (t=14.93 s)

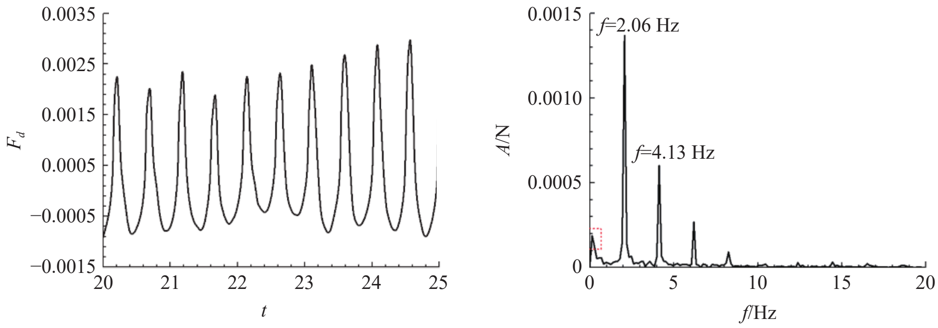
3.2 Effect of wavelength on drag force characteristics

As is known to all, the wavelength is usually complex and variable in the natural environment. The variation in wavelength changes the surrounding flow structure, leading to variations in both the magnitude and frequency of the drag force. To study the pattern of drag force with wavelength, two other kinds of water waves (λ = 30 cm and λ = 25 cm) are selected at a fixed wave height (H = 1.5 cm).

Figure 14 illustrates the time-varying drag force curve and its FFT result for H = 1.5 cm and λ = 30 cm. It shows that the time-averaged amplitude of F_d decreases compared with that at λ = 35 cm (see Figure 6). The FFT result indicates that the fundamental pulsation frequency of the drag force is 2.06 Hz, which is higher than that in the case with λ = 35 cm. Furthermore, there are some low-frequency oscillations in the time-varying drag force curve (see red dashed box in Figure 14b). It is inferred that the decrease in wavelength under identical conditions leads to a reduction in the drag force amplitude, an increase in the fundamental frequency of its fluctuations, and the generation of low-frequency fluctuation components.

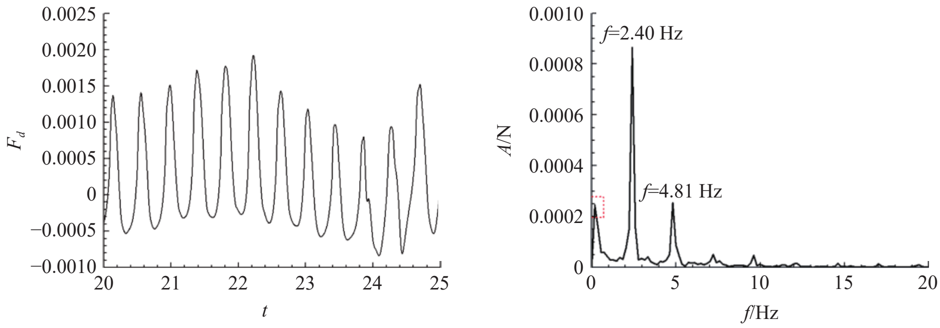
Figure 15 shows the time-varying drag force curve and its FFT result for H = 1.5 cm and λ = 25 cm. It is evident that the time-averaged amplitude of F_d further decreases as the wavelength continues to reduce, and the fundamental pulsation frequency of the drag force also increases. Furthermore, the low-frequency oscillations (see red dashed box in Figure 14b) in the time-varying drag force curve are enhanced as the wavelength continues to decrease.

The above results demonstrate that variations in wavelength generally have a limited impact on the overall system load, such as the drag force on rice seedlings, but they do affect the fluctuation frequency of the drag force, which influences structural fatigue. As the wavelength decreases, the oscillating frequency of the drag force on rice seedlings gradually increases, while low-frequency vibrations are also induced. These disturbances may loosen the root system of the seedlings, reduce soil anchorage strength, and consequently increase the risk of seedling floating. These alterations are expected to substantially influence the mechanical properties of rice seedlings under water wave stress. These findings provide important theoretical support for studies on the rice seedling floating phenomenon and for the development of related agronomic management strategies.



a. Drag force curve b. FFT results

Figure 14 Time-varying drag force curve and its FFT result for H=1.5 cm, λ=30 cm



a. Drag force curve b. FFT results

Figure 15 Time-varying drag force curve and its FFT result for H=1.5 cm and λ=25 cm

3.3 Effect of rice seedling posture on drag force characteristics

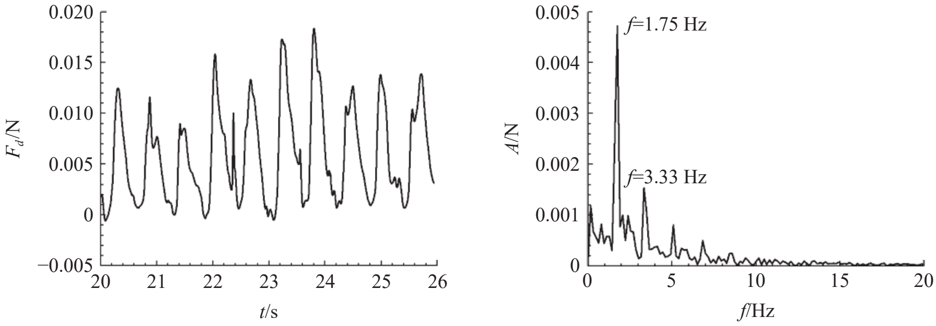
The rice seedling under water wave stress is constantly tilting, and its drag force characteristics change accordingly. To study the pattern of drag force with respect to rice seedling posture, take the wave with H = 3.5 cm and λ = 30 cm as an example. In addition to the upright state, two other inclined angles (30° and 60°) are selected (see Figure 1).

Figure 16 illustrates the time-varying drag force curve and its FFT result for θ = 30°. Compared with the case of the upright state (see Figure 8), the drag amplitude exhibits an increase in fluctuation magnitude at an inclined angle of 30°, accompanied by a marked reduction in its average value. The oscillation frequency of the drag curve is primarily dominated by the fundamental frequency of 1.75 Hz, along with its second harmonic and other low-frequency components.

Figure 17 presents the time-varying drag force curve and its FFT result for θ = 60°. It shows that the drag force amplitude on the rice seedlings increases as the inclined angle increases, which indicates that the rice seedlings at variable inclined angles experience different flow mechanisms. The oscillation characteristics of the drag force curve become more complex. In addition to the fundamental frequency of 1.75 Hz and its second harmonic, disturbances at 5.06 Hz and higher frequencies are rapidly amplified. This means that the increase in the inclined angle has an uncertain influence on the drag force amplitude. It may not increase the drag force amplitude but rather generate a periodic excitation with multiple frequency components acting on the rice seedlings. This process typically leads to loosening of the rice seedling roots and induces a rapid decline in the soil anchorage force of the rice seedlings, resulting in their flotation.

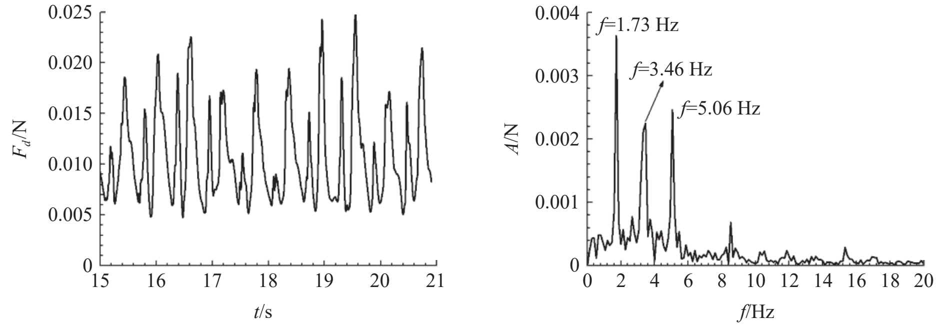
To investigate the mechanism by which inclined angles influence the drag force on rice seedlings, the water volume fraction contour and surface pressure contour of the rice seedling at the peak point of the drag force curve are selected. The analysis focuses on rice seedlings with inclined angles of 30° and 60°. As shown in Figures 18 and 19, when the rice seedlings undergo an increasing tilt, the angle between the direction of water wave diffraction and the seedlings decreases, leading to a reduction in the impact force of the waves on the seedlings. Consequently, the pressure on the windward wave side of the rice seedlings also diminishes. The increase in the inclined angle of a rice seedling changes the flow separation and the evolution of the wake vortex structure on its downstream side, leading to a variation in pressure on its leeward wave side. As a result, the pressure differential between the windward and leeward wave sides also changes, which explains the variation in drag force amplitude with the inclined angle of the rice seedling.

The above results indicate that the variation in rice seedling posture causes changes in the flow structure around them, which leads to variations in the drag force and its oscillation frequency. The unsteady periodic excitation may increase the risk of rice seedlings floating, which is of great significance for studying the mechanical characteristics of rice seedlings under water wave stress.



a. Drag force curve b. FFT results

Figure 16 Time-varying drag force curve and its FFT result with θ=30°



a. Drag force curve b. FFT results

Figure 17 Time-varying drag force curve and its FFT result with θ=60°

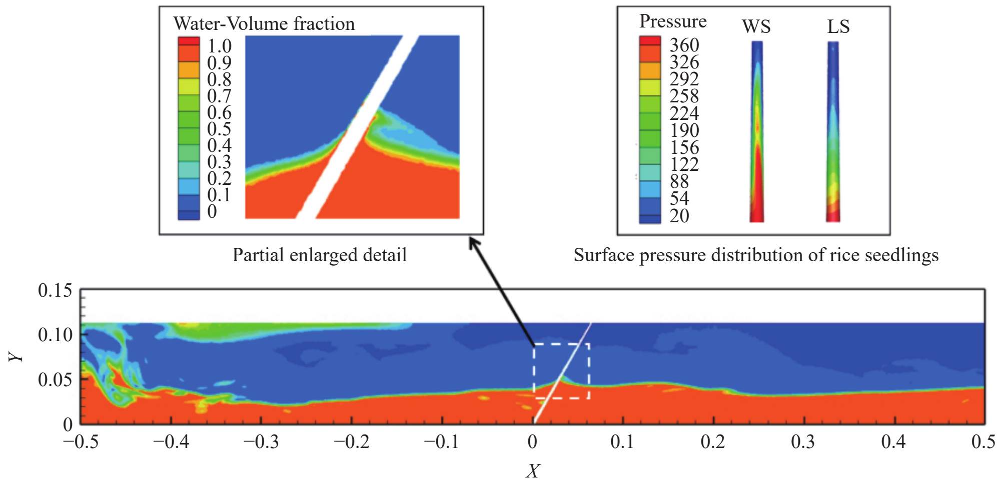


Figure 18 Water volume fraction contour and surface pressure contour of rice seedling at the peak point of drag force curve with θ=30° (t=25.71 s)

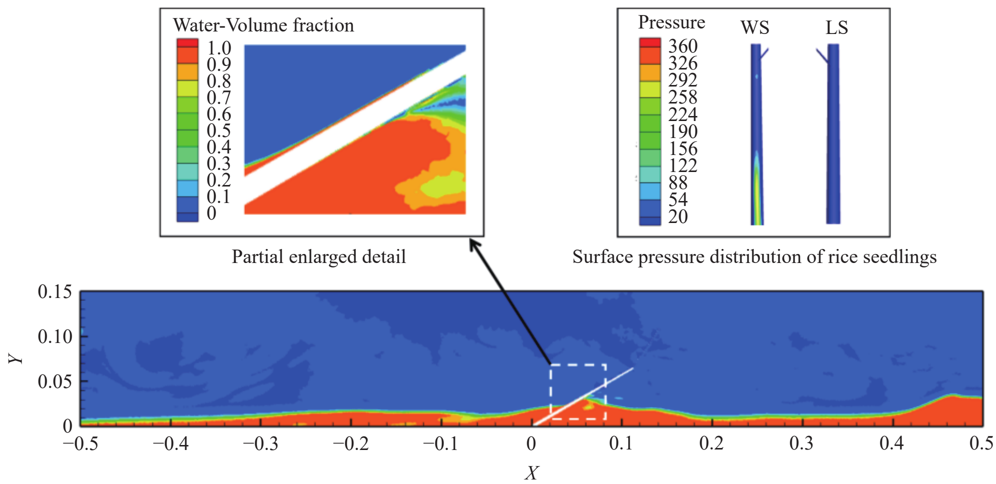


Figure 19 Water volume fraction contour and surface pressure contour of rice seedling at the peak point of drag force curve with θ=60° (t=20.74 s)

4 Conclusions and future work

In this study, unsteady numerical simulations were conducted to investigate rice seedlings under water wave stress. The variation pattern of the drag force on rice seedlings with respect to wave height, wavelength, and plant posture was examined. Based on the results, the following conclusions can be drawn.

1) The wave diffraction induces alterations in flow structures in the downstream of rice seedlings, resulting in distinct pressure distributions on the windward and leeward wave sides of the seedlings. The pressure differential between these surfaces generates the drag force, which varies with the relative position of the wave crest and the rice seedling. The drag force reaches its maximum value when the wave crest reaches the position of the rice seedling. The periodic nature of wave excitation imposes cyclic loading on the rice seedlings, leading to soil loosening around the root zone and reduced anchoring strength, which consequently increases the risk of the rice seedling floating. Under constant wavelength conditions, an increase in wave height enlarges the effective force-acting area on the rice seedlings, thereby amplifying the magnitude of the drag force. When wave height increases to the point of wave breaking, the ensuing broken waves impose significant additional impact loads on the rice seedlings, causing a sharp increase in drag force and further elevating the risk of the rice seedling floating.

2) Under conditions of constant wave height, a decrease in wavelength alters the mechanism of wave action on rice seedlings, leading to a reduction in the amplitude of resistance. However, it concurrently increases the fundamental frequency of wave load oscillations and excites new low-frequency excitations. These disturbances may loosen the root system of the seedlings and reduce soil anchorage capacity, which consequently increases the risk of seedling floating.

3) Under identical conditions, an increase in the inclination angle of rice seedlings alters the surrounding flow mechanism, which has an uncertain effect on the drag force amplitude. Furthermore, it induces an increase in the fundamental frequency of wave load oscillation and excites new frequency excitations, resulting in complex frequency characteristics of the drag force. These fluctuating loads can readily trigger soil loosening, thereby significantly increasing the risk of rice lodging.

Based on the above conclusions, it can be observed that after rice seedling transplantation, wave breaking in paddy fields should be minimized as much as possible to reduce the sudden increase in wave-induced drag force on the rice seedlings. To suppress wave breaking, the water depth in the paddy field can be appropriately increased within allowable limits, or field management measures can be adopted to reduce the ratio of wave height to wavelength. In addition, monitoring equipment can be installed in the paddy field to detect wave breaking conditions and thereby assess the risk of rice seedling floating.

In future studies, a fully coupled fluid-structure interaction (FSI) model will be developed to investigate the dynamic behavior of rice seedlings under wave-induced loads. This model will integrate computational fluid dynamics (CFD) simulations with finite element analysis (FEA) to capture large deformations of seedling structures and their feedback effects on surrounding flow fields. Furthermore, the role of root-soil anchorage failure modes during resonance events will be analyzed through dynamic soil stress measurements. These investigations aim to establish a mechanistic understanding of how wave periodicity and amplitude modulate seedling stability.

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