Sprinkler droplet impact angle affects shear stress distribution on soil surface – a case study of a ball-driven sprinkler

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ABSTRACT

Droplet shear stress is the main cause of soil erosion under sprinkler irrigation, and the effect of droplet impact angle on the shear stress distribution cannot be ignored. In this study, a ball-driven sprinkler was selected to investigate the radial distributions of droplet impact angles under three operating pressures (0.25, 0.30, and 0.35 MPa) and two nozzle diameters (1.9 and 2.2 mm), which are commonly used in agricultural irrigation. The effect of droplet impact angles on the distances from the sprinkler, droplet impact velocities, and shear stresses were analyzed by a 2DVD instrument. Irrespective of the nozzle diameter or operating pressure, the droplet velocities and impact angles near the sprinkler were distributed at 1.0–5.5 m s⁻¹ and 70–90°, respectively, and the droplet shear stress increased with the distance from the sprinkler. Suitable operating pressure and distance from the sprinkler significantly reduced the droplet shear stress. Although the nozzle diameter had a certain effect on the maximum shear stress, the overall effect was insignificant. We developed the models for the radial distribution of droplet shear stresses, which were in good agreement with the measurement. This study proposes a new method for accurately predicting the soil erosion under sprinkler irrigation.

Key words | ball-driven sprinkler, droplet impact angle, droplet impact velocity, droplet shear stress, sprinkler irrigation

HIGHLIGHTS

- The soil erosion risk at the end of the spray jet is highly related to droplet shear stress rather than droplet kinetic energy.
- Increasing the operating pressure or decreasing the nozzle diameter can effectively reduce the maximum droplet shear stress.
- Mathematical models are developed for predicting the radial distribution of droplet shear stress.

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INTRODUCTION

As a high-efficiency water-saving irrigation technique, sprinkler irrigation has been developed, promoted, and applied in China since the 1950s (Yan et al. 2020). By the end of 2018, China’s sprinkler irrigation area has reached 4.4 million hm², accounting for about 20% of the total area under high-efficiency water-saving irrigation. Soil surface sealing or crust formation caused by sprinkler irrigation is common (Chang & Hills 2006). It not only reduces the water infiltration rate, but also leads to surface runoff. Previous studies have shown that soil particle detachment is the main reason for soil surface sealing (Assouline & Ben-Hur 2009) and generally related to droplet kinetic energy (Yan et al. 2011; Caracciolo et al. 2012). However, some studies (Huang et al. 1982; Ghadiri & Payne 2010) showed that from a mechanism perspective, the soil particle detachment from aggregates is caused by external shear stress rather than droplet kinetic energy.

Several studies have been conducted on the stress distribution due to the droplet impact on the soil surface and the soil particle decomposition. Ghadiri & Payne (1986), based on the water-hammer theory, calculated the compressive stress of falling raindrops and shear stress caused by the flow impact. They found that the lateral shear stress was several times larger than the compressive stress. In another study, Huang et al. (1982) used the Marker and Cell (MAC) numerical technique to simulate the impact of raindrops on a rigid surface. The results showed that the impact pressure distribution was non-uniform. The maximum pressure occurred at the contact circumference, and the rebound velocity on the rigid surface was twice the impact velocity. Ferreira et al. (1985) applied a modified SOLA-VOF numerical simulation scheme for simulating the raindrop’s impact in a deep pool based on energy balance. Their results indicated that most of the soil aggregate fragmentation occurred during the development of the crater, mostly due to the impact pressure and shear on the bottom of the pool.

The studies mentioned above mainly focused on the vertical impact of raindrops, which was quite different from sprinkler irrigation, where droplets hit the soil at oblique angles. Chang & Hills (1993b) developed a numerical simulation model for studying the pressure and shear stress distribution on a soil surface following sprinkler droplet impact. Simulation analysis indicated that the oblique droplet impact decreased the magnitude of the impact force, but it increased the shear stress, compared with the vertical droplet impact. In another study, Chang & Hills (1995a) investigated the influence of sprinkler droplet impact angles on soil infiltration through laboratory experiments. They found that the average steady infiltration rates for all soil types increased in the following order of the impact angle: 60°, 45°, and 90°, which implied that the effects of sprinkler droplet impact angle on the shear stress distribution and soil infiltration need to be considered. However, in their research, only three droplet impact angles (90°, 45°, and 60°) were selected, which was insufficient to reflect the impact of water droplets on the ground at multiple angles. Hence, the effect of droplet impact angle on the shear stress distribution needs to be further investigated.
The sprinkler is an important component of a sprinkler irrigation system, and its performance directly affects the quality of the whole system (Zhu et al. 2022; Zhang et al. 2019). With the development of the low-pressure and energy-saving sprinkler irrigation technology, it is critical to develop sprinklers with simple structures at low operating pressure. In recent years, a ball-driven sprinkler that uses a stainless-steel ball to drive the nozzle to rotate and spray has been successfully applied in field crop irrigation (Hui et al. 2019). However, there are still few reports on the effects of droplet impact angle on the shear stress distribution of a ball-driven sprinkler. In this context, the main objectives of this study were (1) to investigate the radial distributions of droplet impact angles for the ball-driven sprinkler under three operating pressures (0.25, 0.30, and 0.35 MPa) and two nozzle diameters (1.9 and 2.2 mm); (2) to establish the relationships between the droplet impact angle and distance from the sprinkler, droplet velocity, and shear stresses, respectively; and (3) to further develop the models for the radial distribution of droplet shear stresses, validated by experimental data.

MATERIALS AND METHODS

Experimental setup

Figure 1 shows the flowchart of the experiment process. The experiment was performed indoors to avoid the impacts of wind. Figure 2 shows the experimental setup. We used a ball-driven sprinkler with an inlet diameter of 12.7 mm, which is not only simple in its structure and easy to clean, but also has a good application uniformity (Hui et al. 2019). The components of the sprinkler include a nozzle (diameter of 1.9 or 2.2 mm), a chamber (the space enclosed by the upper and lower parts of the sprinkler.
body), a guide structure (with an inlet angle of 18.5°), a stainless-steel ball (diameter of 7.8 mm), and rotating components (Figure 3). During the sprinkler test, water enters the chamber via the guide structure and forms the high-speed water flow, impacting the stainless-steel ball. The ball circularly moves and continuously hits the flange connected to the nozzle, therefore the nozzle rotates and sprays.

In this experiment, the ball-driven sprinkler was mounted on a vertical riser with a height of 1 m, and its operating pressure ranged from 0.25 to 0.40 MPa. A pressure transducer (Xi’an Xinmin model CYB, accuracy of ±0.1%), with a range from 0 to 0.50 MPa, was installed at the sprinkler inlet and connected to a data logger to monitor the sprinkler pressure every 5 s. In addition, a two-dimensional video disdrometer (2DVD), developed by Joanneum Research Corp, Austria, was used to measure the droplet diameter and velocity (Figure 4). Two vertically disposed CCD cameras inside the instrument made linear scans of the droplets passing through the measurement area (100 × 100 mm²), recording individual droplet diameter as well as the vertical and horizontal velocity components (Huang et al. 2010; Ge et al. 2018). The test accuracy of the droplet diameter was 0.19 mm.

**Experimental design**

The operating pressure and nozzle diameter of the sprinkler were considered in the radial test of water droplets. Three operating pressures were chosen according to manufacturer’s recommendation, namely 0.25, 0.30, and 0.35 MPa. Also, the two nozzle diameters of 1.9 and 2.2 mm that are commonly used in agricultural irrigation were chosen for testing. In total, six trials were performed, each with three replicates. In each trial, the measuring points were set at 1-m intervals along the radial direction, and the diameters and velocities of the sprinkler droplets falling on each measuring point were monitored by the 2DVD, as shown in Figure 2. The number of the droplets collected at each measuring point was at least 10,000. All the measurements were taken when

![Figure 3](image1.png)

**Figure 3** | Diagram of the sprinkler used in the experiment: 1. lower part of the sprinkler body, 2. stainless-steel ball, 3. upper part of the sprinkler body, 4. nozzle, 5. rotating components, 6. guide structure.

![Figure 4](image2.png)

**Figure 4** | Photograph of the 2DVD instrument (a) and schematic presentation of the measuring planes of 2DVD (b).
the pressure was kept stable. Indoor air and water temperature were approximately 30 and 26 °C, respectively, and relative humidity was 60%. The following design standards were adopted in the present experiment: ISO 7749-2 (ISO Standards 2004) and ISO 15886-3 (ISO Standards 2012).

Calculation of resultant droplet velocity, impact angle, and shear stress

Since the vertical ($V_v$) and horizontal ($V_h$) velocities of a water droplet could be recorded by the 2DVD, the calculation equation for the resultant velocity ($V$) of a water droplet was as follows:

$$ V = \sqrt{V_v^2 + V_h^2} $$  \hspace{1cm} (1)

The impact angle ($\theta$) of a water droplet was obtained by the following equation:

$$ \theta = \frac{180}{\pi} \arctan \left( \frac{V_v}{V_h} \right) $$  \hspace{1cm} (2)

where $V$ is the resultant droplet velocity, m·s$^{-1}$; $\theta$ is the droplet impact angle, °; $V_v$ is the vertical droplet velocity, m·s$^{-1}$; and $V_h$ is the horizontal droplet velocity, m·s$^{-1}$.

The shear stress ($S$) of a water droplet in this study was defined as the following formula (Ghadiri & Payne 1986):

$$ S = 0.5 \rho V_h^2 $$  \hspace{1cm} (3)

where $S$ is the droplet shear stress, N m$^{-2}$; $\rho$ is the droplet density, kg m$^{-3}$.

Data analysis

The coefficient of variation (CV) was used to evaluate the dispersion degree of droplet impact angles at different distances from the sprinkler (Liu et al. 2016). A higher CV value indicated that the droplet impact angle distribution was more discrete. Regression analysis, using the Origin 8.5 software (OriginLab, Northampton, MA, USA), was employed to analyze the relationships between droplet impact angles and the distances from the sprinkler, droplet velocities, and shear stresses, respectively. The coefficient of determination ($R^2$) (Zapata et al. 2018) was used to evaluate the fitting performance of the regression models (a higher $R^2$ value means a higher model accuracy). The regression analysis was also applied to develop the radial distribution models of droplet shear stresses. The root mean square error (RMSE) and the normalized root mean square error (NRMSE) between the calculated and measured values were used to verify the accuracy of the distribution models (Zheng et al. 2018). The lower values of RMSE and NRMSE corresponded to the higher accuracies of models in predicting droplet shear stresses. Additionally, the effects of operating pressure, nozzle diameter, and distance from the sprinkler on droplet shear stresses were each subjected to multi-way analysis of variance (ANOVA). Means were separated using Fisher’s Protected LSD at the 0.05 level via the software package SPSS 20.0 (IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

Radial distribution of droplet impact angles

The droplet impact angle is closely related to the distribution of the droplet shear stress and the soil infiltration (Hattori & Kakuichi 2013). Figure 5 presents the radial relative frequency distributions of droplet impact angles under three operating pressures and two nozzle diameters. Within 4 m of the sprinkler, nearly 100% of the droplet impact angles were distributed in the range of 70–90°, regardless of nozzle diameters and operating pressures. Within 2 m of the sprinkler, nearly 100% of the droplet impact angles were distributed in the range of 70–90°, regardless of nozzle diameters and operating pressures. This revealed that large droplet impact angles usually appeared near the sprinkler, in good agreement with the results reported by Chang & Hills (1993a). One possible explanation for this phenomenon is that many small droplets occurred near the sprinkler. For the distances of 2 and 4 m away from the sprinkler, the relative frequencies of droplets with a diameter of 0–2 mm were close to 100% under different treatments (Table 1). Smaller droplets had a larger specific surface area (surface area per unit volume), resulting in a higher air friction resistance ratio, which in turn made the horizontal droplet velocity quickly approach zero. Therefore, the horizontal distances traveled by smaller droplets
were shorter, and their impact angles were almost perpendicular to the horizontal plane.

With increasing distance from the sprinkler, the number of droplets with an impact angle of 70°–90° gradually decreased, and that of droplets with an angle below 70° increased, resulting in a dispersed distribution of droplet impact angles. For instance, when the distance from the sprinkler reached 10 m, the CV values of droplet impact angles at the operating pressure of 0.25 MPa were 17.6% and 22.4% for the nozzle diameters of 1.9 and 2.2 mm, respectively. These values increased by 10.9 and 16.4 percentage points, respectively, compared to the 2 m distance (Table 2). This implied that the end of the spray jet was probably a most vigorous area for sprinkler jet and droplet breakup and for droplets colliding

Table 1 | Relative frequency distributions of droplet diameters along the spray direction under three operating pressures and two nozzle diameters

| Operating pressure (MPa) | Droplet diameter (mm) | Relative frequency (%) |
|--------------------------|-----------------------|------------------------|
|                          | 1.9 mm                | 2 m  4 m  6 m  8 m  10 m | 2 m  4 m  6 m  8 m  10 m |
|                          |                       | 0–1  1–2  2–3  3–4     | 0–1  1–2  2–3  3–4     |
| 0.25                     | 1.9 mm                | 99.3  97.0  66.2  14.6  21.5 | 99.7  92.6  10.0  16.5  56.0 |
|                          | 2.2 mm                | 0.7   3.0   33.7  80.3  51.8 | 0.3   7.4   86.7  73.8  8.0 |
| 0.30                     | 1.9 mm                | 98.6  95.9  29.9  12.4  24.6 | 99.7  95.7  19.4  11.1  61.6 |
|                          | 2.2 mm                | 1.2   4.1   69.7  69.1  46.7 | 0.3   4.3   79.6  81.1  4.8 |
| 0.35                     | 1.9 mm                | 99.7  94.0  54.3  27.4  14.7 | 99.5  91.8  50.5  19.4  16.9 |
|                          | 2.2 mm                | 0.3   6.0   45.5  70.7  73.6 | 0.5   8.2   48.9  80.1  60.8 |
|                          |                       | 0    0    0.2   1.9   10.9 | 0    0    0.6   3.0   23.7 |
|                          |                       | 0    0    0    0     0.8 | 0    0    0    0     0.9 |

Figure 5 | Radial distributions of droplet impact angles under three operating pressures and two nozzle diameters.
with each other, thereby resulting in a more dispersed distribution of droplet impact angles. Similar observations have been obtained by Zhang et al. (2018) and Hui et al. (2019) on the droplet size distribution.

Further analysis of Figure 5 indicated that when the sprinkler pressure was 0.35 MPa, the relative frequencies of two nozzles, impact angles of 70–90°, remained above 88% at the distance of 8 m from the sprinkler, far greater than for the other two pressures. Taking the nozzle diameter of 2.2 mm as an example, for 0.35 MPa, the relative frequency of droplet impact angles within 70–90° could reach 90.2% at the distance of 8 m, whereas the frequencies were only 44.7% and 56% for 0.25 and 0.30 MPa, respectively. This showed that raising the sprinkler working pressure might contribute to increasing the impact angles of water droplets at a location away from the sprinkler. This result was not surprising, since higher sprinkler operating pressures generated smaller droplets and faster initial ejecting velocities, which might carry the smaller droplets to a farther location. As shown in Table 1, at the distances of 8 and 10 m from the sprinkler, the 1.9 mm nozzle’s relative frequencies of small droplets (0–2 mm) were higher by 3.2 and 15.0 percentage points under 0.35 MPa than under 0.25 MPa, respectively. The above values changed to 6.7 and 11.4 percentage points with the 2.2 mm nozzle, respectively. The observations of Hills & Gu (1989) and Zhu et al. (2012) also supported this finding.

The effect of nozzle diameter on the droplet impact angle was not significant (P > 0.05, results not presented) at the same operating pressure and measuring point, which was in good agreement with the results reported by Chang & Hills (1993a). This was partly because larger nozzles generated larger droplet sizes. Thus, the loss ratios of air resistance decreased. Simultaneously, larger nozzles also had less friction losses, which increased the initial ejecting velocities. Hence, the sum of these two effects appeared to be zero, which has also been found by Hills & Gu (1989).

### Relationship between droplet impact angle and distance from the sprinkler

To further determine the relationship between droplet impact angle and distance from the sprinkler, the radial distributions of average droplet impact angles under three operating pressures and two nozzle diameters were analyzed and are depicted in Figure 6. The maximum average droplet impact angle appeared at the distance of 4 m, irrespective of nozzle size and working pressure. This could be explained by the previous findings that nearly all droplet impact angles were distributed within 70–90° at this distance. With increasing distance from the sprinkler, the average droplet impact angles under each treatment continuously tapered off and finally reached the lowest values at 10 m. This outcome suggested that if water droplets had the same diameter and velocity, the droplets located farther away from the sprinkler might generate greater shear stresses due to their lower impact angles. This result explained why the area at the end of the sprinkler jet was prone to soil erosion (King & Bjorneberg 2011; Yan et al. 2011).

According to regression analysis results, the average droplet impact angle and the distance from the sprinkler showed a good linear relationship (the mean of $R^2$ under all working conditions was 0.850, Figure 6) for three operating pressures and two nozzle diameters, which could be expressed by Equation (4):

$$\theta_a = al + b$$  (4)
where \( \theta_a \) is the average droplet impact angle, \(^\circ\); \( l \) is the distance from the sprinkler, m; \( a \) and \( b \) are the coefficients in the equation.

Notably, the coefficients \( a \) and \( b \) in Equation (4) for the nozzle diameters of 1.9 and 2.2 mm could be represented as the linear fitting equations of the operating pressure \( (p) \), respectively.

For the 1.9 mm nozzle diameter, the expressions were as follows:

\[
a = 7.90p - 3.75 \quad (R^2 = 0.760) \tag{5}
\]

\[
b = -32.50p + 94.41 \quad (R^2 = 0.780) \tag{6}
\]

Therefore, substituting Equations (5) and (6) into Equation (4), the average droplet impact angle could be expressed as an equation of the distance from the sprinkler and operating pressure:

\[
\theta_a = 7.90pl - 3.75l - 32.50p + 94.41 \tag{7}
\]

For the 2.2 mm nozzle diameter, the expressions were as follows:

\[
a = 2.50p - 1.96 \quad (R^2 = 0.999) \tag{8}
\]

\[
b = -9.60p + 85.97 \quad (R^2 = 0.945) \tag{9}
\]

Similarly, substituting Equations (8) and (9) into Equation (4), the average droplet impact angle could be expressed as an equation of the distance from the sprinkler and operating pressure:

\[
\theta_a = 2.50pl - 1.96l - 9.60p + 85.97 \tag{10}
\]

**Relationship between droplet impact angle and droplet velocity**

Droplet impact velocity is a key factor affecting the droplet shear stress, and a high droplet velocity has a higher potential to detach soil particles. Figure 7 presents the relationships between droplet impact angles and velocities for various distances to the sprinkler with three operating pressures and two nozzle diameters. Overall, droplet impact angles increased initially near the sprinkler and then decreased, with higher droplet velocities at a position far away from the sprinkler, irrespective of the nozzle pressure or diameter. When the distance from the sprinkler was 2 m, the droplet velocities and impact angles under different working conditions were mainly distributed at 1.0–5.5 m s\(^{-1}\) and 70–90\(^\circ\), respectively. As the distance increased to 4 m, the distribution range of droplet velocity further expanded, whereas the impact angle distribution remained unchanged. Nevertheless, the mean droplet impact angle at this distance increased slightly relative to the distance of 2 m. Taking the 1.9 mm nozzle diameter as an example, the average droplet impact angles were 0.8\(^\circ\), 0.1\(^\circ\), and 1.0\(^\circ\) higher at 4 m than those at 2 m (80.1\(^\circ\), 81.4\(^\circ\), and 79.3\(^\circ\)) for 0.25, 0.30, and 0.35 MPa, respectively.

With the gradual increase of the distance, the distribution range of droplet velocities expanded continually, but the impact angles of some water droplets began to
decrease. At a distance of 6 m, both nozzles’ droplet velocity ranges increased to 1.0–6.2 m s\(^{-1}\) for three operating pressures, while their droplet impact angles were gradually shifted to the range of 60–70°. When the distance reached 10 m, each treatment attained the maximum on the distribution range of droplet velocities, which was 1.0–7.8 m s\(^{-1}\). Correspondingly, the droplet impact angles under various working pressures (0.25, 0.30, and 0.35 MPa) were finally stabilized at around 68.2°, 70.5°, and 72.9° for 1.9 mm and 70.6°, 70.7°, and 71.2° for 2.2 mm. The above results implied that farther away from the sprinkler, greater droplet shear stresses occurred due to higher droplet velocities and smaller impact angles. This confirmed once again that susceptibility to soil erosion at the end of the spray jet was actually closely related to the large droplet shear stress rather than simply attributed to the large droplet kinetic energy (Ghadiri & Payne 2010).

Additionally, the distributions of average droplet impact angles with the average droplet velocities under three operating pressures and two nozzle diameters were analyzed and are depicted in Figure 8. Likewise, average droplet impact angles showed a strong linear relationship (the mean of \(R^2\) under all working conditions was 0.880) with the average droplet velocities for different irrigation treatments, and

![Figure 8](image-url)
their linear equations were expressed as follows:

\[ \theta_a = c V_a + d \]  

where \( V_a \) is the average droplet velocity, m s\(^{-1}\); \( c \) and \( d \) are the coefficients in the equation.

After removal of the coefficients \( c \) and \( d \), using a step-wise linear regression procedure, the relationships of \( \theta_a \) with \( p \) and \( V_a \) for the two nozzles were determined using the following equations.

For the nozzle diameter of 1.9 mm,

\[ \theta_a = 24.50pV_a - 11.44V_a - 73.60p + 113.90 \]  

For the nozzle diameter of 2.2 mm,

\[ \theta_a = 10.90pV_a - 7.00V_a - 29.70p + 99.08 \]

**Relationship between droplet impact angle and droplet shear stress**

Droplet shear stress is a major contributor to soil surface crusting (Ghadiri & Payne 1986). Figure 9 presents the relationships between droplet impact angles and shear stresses for different sprinkler working conditions. Obviously, a greater distance from the sprinkler resulted in an increased droplet shear stress, and the peak shear stresses of all irrigation treatments appeared at the end of the spray jet (10 m). For operating pressures of 0.25, 0.30, and 0.35 MPa, the maximum droplet shear stresses (the largest values of shear stresses among all water droplets measured in the test) for a nozzle diameter of 1.9 mm were 9,874.0, 8,865.0, and 7,226.5 N m\(^2\), respectively. The corresponding values for the 2.2 mm nozzle were 10,798.4, 9,682.9, and 7,246.1 N m\(^2\), respectively. These data revealed that the maximum shear stresses at 2.2 mm were above those at 1.9 mm, and the maximum values gradually decreased as operating pressures increased. This finding fully explained that increasing the sprinkler pressure or decreasing the nozzle size could effectively lessen the upper limit of droplet shear stresses, although the effect of nozzle size on the impact angle distribution was not significant. The main reason for this phenomenon was that the decrease of the nozzle size reduced droplet impact velocities, and therefore the shear stresses correspondingly tapered off, although the droplet impact angle was only slightly changed (Ghadiri & Payne 1986).

Based on Figure 9, with a larger droplet impact angle, the shear stress decreased, irrespective of the nozzle diameter and the operating pressure. This implied that the droplet impact angle was closely related to the shear stress, which was in line with the results reported by Chang & Hills (1993a, 1993b). Through regression analysis, we found a strong quadratic relationship between the droplet shear stress and impact angle, with an average \( R^2 \) value of 0.916 (Figure 9). The quadratic equation could be expressed as follows:

\[ S = f \theta^2 + g \theta + h \]  

where \( f \), \( g \), and \( h \) are the coefficients in the equation.

Due to the good linear relationships between \( p \) and coefficients \( f \), \( g \), and \( h \), the equations of \( S \) with \( p \) and \( \theta \) for the two nozzles could be calculated by Equations (15) and (16), respectively.

For the 1.9 mm diameter, the equation was as follows:

\[ S = -8p \cdot \theta^2 + 10.61\theta^2 + 1207p \cdot \theta - 1740.70\theta \\
- 44700p + 71104 \]  

For the 2.2 mm diameter, the equation was as follows:

\[ S = -21.30p \cdot \theta^2 + 14.75\theta^2 + 3223p \cdot \theta - 2368.30\theta \\
- 119210p + 94452 \]

**Model for the radial distribution of droplet shear stresses**

Scientific prediction of the radial distribution of droplet shear stresses is of great significance for optimizing sprinkler irrigation systems and reducing soil erosion risk. Figure 10 presents the distribution models of average droplet shear stresses (\( S_a \)) along the spray direction under three operating pressures and two nozzle diameters. These models could be expressed in the form of...
an exponential equation $S_a = je^{k_1}$, where $j$ and $k$ are the coefficients. In each treatment, the average droplet shear stress increased with increasing distance from the sprinkler and decreased with decreasing operating pressure, which was consistent with the above results of the maximum shear stress.

In addition, as the operating pressure ($p$) had a great impact on the hydraulic performance of the sprinkler (Zhang et al. 2013), the following mathematical models could be attained after the coefficients $j$ and $k$ in the exponential equation were gradually replaced with $p$, according to the regression analysis.
For the 1.9 mm diameter:

\[ S_a = (5619.20 p^2 - 3132.30 p + 470.81)e^{-32.16 p^2 - 18.19 p - 2.1132} \]  

(17)

For the 2.2 mm diameter:

\[ S_a = (-4265 p^2 + 2556.1 p - 313.46)e^{8.38 p^2 - 5.605 p - 1.2762} \]  

(18)

To verify the accuracy of the models, the comparisons between the measured and calculated values of droplet shear stresses for both nozzle diameters are shown in Figure 11. The results indicated that the calculated values were in good agreement with the measured values, and their RMSE and NRMSE values were 115.5 N m\(^{-2}\) and 12.6% for 1.9 mm, respectively, and 134.9 N m\(^{-2}\) and 15.3% for 2.2 mm, respectively. Consequently, the prediction models proposed in this paper were relatively reliable and could be recommended for predicting the ball-driven sprinkler’s radial distribution of droplet shear stresses under different operating pressures and nozzle sizes.

**Analysis of variance of the effects of various factors on droplet shear stress**

To further determine the influences of various factors (operating pressure, nozzle diameter, and distance from the sprinkler) on the droplet shear stress, we performed...
ANOVA for the effect of each factor (Table 3). The droplet shear stress was significantly affected by the operating pressure and distance from the sprinkler \((P = 0.000)\), whilst the effect of the nozzle diameter was non-significant \((P = 0.115)\). These findings suggested that selecting a reasonable working pressure and sprinkler arrangement was essential to reduce the shear stress of water droplets and improve the performance of sprinkler irrigation systems. Although the nozzle diameter had a certain effect on the maximum value of the shear stress, the overall effect was not large.

**CONCLUSIONS**

Regardless of the nozzle diameter and operating pressure, the droplet impact angles in the range of 70°–90° basically occurred within 4 m of the sprinkler. With increasing distance from the sprinkler, the higher droplet shear stress was obtained due to the increased droplet velocity and decreased impact angle. This confirmed that the soil erosion risk at the end of the spray jet was highly related to large droplet shear stresses. Moreover, the prediction models for the radial distribution of droplet shear stresses were developed using the droplet velocity and impact angle data measured by the 2DVD instrument. These models greatly improved the convenience of predicting a ball-driven sprinkler’s droplet shear stress and facilitated the design optimization of the sprinkler irrigation system.

Based on the ANOVA results, the operating pressure and distance from the sprinkler significantly impacted the droplet shear stress. This finding revealed that the determination of a reasonable sprinkler working pressure and arrangement was crucial to reduce droplet shear stresses and improve the quality of sprinkler irrigation systems. Although the maximum shear stress was affected by the nozzle diameter, the overall effect was not large.

Our findings provide a new method for accurately predicting the soil erosion under sprinkler irrigation, and a basis for optimizing the working parameters of the sprinkler irrigation system. However, due to the unique structure of the ball-driven sprinkler, it may not be suitable for other typical sprinkler types, such as the impact sprinkler, fixed spray plate sprinkler and rotating spray plate sprinkler, etc., so further research is deserved. Besides, this study does not involve the relationship between the droplet shear stress and soil infiltration rate, which still needs to be determined.

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**DECLARATION OF CONFLICTS OF INTEREST**

The authors declare that they have no conflicts of interest.

**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

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