Research Article

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Two-dimensional flow field distribution characteristics of flocking drainage pipes in tunnel

<https://doi.org/10.1515/phys-2020-0013>

received January 16, 2020; accepted February 25, 2020

Abstract: With the rapid development of traffic infrastructure in China, the problem of crystal plugging of tunnel drainage pipes becomes increasingly salient. In order to build a mechanism that is resilient to the crystal plugging of flocking drainage pipes, the present study used the numerical simulation to analyze the two-dimensional flow field distribution characteristics of flocking drainage pipes under different flocking spacings. Then, the results were compared with the laboratory test results. According to the results, the maximum velocity distribution in the flow field of flocking drainage pipes is closely related to the transverse distance h of the fluff, while the longitudinal distance h of the fluff causes little effect; when the transverse distance h of the fluff is less than $6.25D$ (D refers to the diameter of the fluff), the velocity between the adjacent transverse fluffs will be increased by more than 10%. Moreover, the velocity of the upstream and downstream fluffs will be decreased by 90% compared with that of the inlet; the crystal distribution can be more obvious in the place with larger velocity while it is less at the lower flow rate. The results can provide theoretical support for building a mechanism to deal with and remove the crystallization of flocking drainage pipes.

Keywords: tunnel, flocking drainage pipe, flow field, villi spacing

1 Introduction

Engineering diseases are gradually emerging with the rapid development of highway transportation infrastructure in China. According to the engineering investigation, during the construction (Figure 1) and operation (Figure 2), crystal blocking occurs in the drainage pipe, which will pose potential risks to the tunnel operation if not handled in time. Once the drainage pipe is completely blocked, groundwater cannot be discharged smoothly, and the water pressure on the lining will increase. Accordingly, the safety of the lining structure will be reduced. Fortunately, this problem has gradually attracted attention of the engineering circle. The engineering circle has carried out research on the prevention and treatment technology of drainage pipes. Flocking drainage pipe is a new technology for preventing the blocking from crystallization. It is composed of ordinary drainage pipe and villi (round sections) on the inner wall (Figure 3). Natural phenomena provide the inspiration for designing this type of drainage pipe, that is, the rains on the cable will not increase despite the increase in raining time. When the volume of raindrops exceeds a certain amount, the rains will drop.

Figure 1: The railway tunnels of Chongqing under construction.

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Figure 2: Operation of metro tunnels in Chongqing.

Figure 3: Cross section of flocking drainage pipe.

A large number of laboratory tests have proved that the flocking drainage pipe can prevent crystal blocking [1–3], but the technical principles need to be further explored and studied, including how to distribute the flow field in the process of water flow in the flocking drainage pipe.

In short, the groundwater flow in flocking drainage pipes is a circular flow movement, a problem that widely exists in water conservancy, construction and environmental engineering. Wu *et al.* [4] pointed out that the existing studies mainly focus on the bearing characteristics and the wake flow field structure of single and double cylinders under simple conditions. Hu *et al.* [5] studied the characteristics of flow around cylinders arranged in series with unequal diameters. Zhou *et al.* [6] carried out visualization experiments on flow around cylinders arranged in tandem with different spacing ratios. Cui *et al.* [7] studied the interference effect between cylinders arranged in series in a uniform flow field. Sun *et al.* [8] analyzed the influence of slit in the flow around cylinders arranged in tandem.

Yang *et al.* [9] studied the time-averaged pressure distribution and aerodynamic force of the flow around a single cylinder, two cylinders in tandem with different spacings and three cylinders in series by using the wind tunnel test method of rigid model pressure. Pang *et al.* [10] established a numerical calculation model of flow around double cylinders based on instantaneous vorticity conserved boundary conditions based on the characteristics of double cylinders in tandem. Du *et al.* [11] studied the aerodynamic performance and the variation of flow field characteristics of parallel double cylinders with the ratio of cylinder spacing P/D (P refers to the center spacing, and D is the diameter of cylinder) at high Reynolds numbers ($Re = 1.4 \times 10^5$) based on the large eddy simulation (LES) method. Yu *et al.* [12,13] studied the influence of staggered angle B on the flow characteristics of two cylinders with unequal diameters under the condition of low subcritical Reynolds number and the influence of the change of chamfer radius on the flow dynamic characteristics of the cylinders. Yang *et al.* [14] adopted the embedded iterative immersed boundary method to simulate the flow around three cylinders arranged in equilateral triangles. Li *et al.* [15] simulated the flow around the cylinder at high Reynolds numbers using the improved delayed vortex separation method. In addition, Huang *et al.* [16] numerically simulated the flow around a circular cylinder with an elastic separation plate at a Reynolds number of 100. Xing and Sun [17] studied the flow around a slotted cylinder in an infinite flow field with a low Reynolds number based on the numerical simulation method. Du *et al.* [18] used the finite volume method to simulate the flow around a square cylinder at a Reynolds number of 22,500 and chamfer radiuses of $0.1D$ (D is the side length of the square cylinder), $0.2D$ and $0.3D$. Wang *et al.* [19] made a numerical simulation of two-dimensional flow around a circular cylinder in a curved channel at a low Reynolds number. Besides, Wang *et al.* [20] applied the numerical model of LES and adopted vortex identification to simulate the flow around a three-dimensional finite length cylinder. They then verified and analyzed the flow. Sun *et al.* [21] researched the flow around a circular cylinder with a jet at the front stagnation point. Hu *et al.* [22] used the computational fluid dynamics method to simulate the flow of pollutants around two cylinders under different arrangements at $Re = 1 \times 10^6$. Yan *et al.* [23] conducted two-dimensional numerical simulations for the interaction of the flow between a moving cylinder row and a fixed single cylinder based on the dynamic grid technology under $Re = 3,900$.

At present, the research on the flow around a circular cylinder mainly focuses on the flow pattern

and stress-bearing characteristics of a single cylinder, double cylinders and a group of cylinders, with a high Reynolds number. Therefore, most of the flow patterns are turbulent. At low Reynolds numbers, the millimeter size of the cylinder section, the laminar flow state, distributing the flow field in the flocking drainage pipe becomes the key research area. This study aims at the flow around multiple cylinders with a horizontal spacing ratio of villus center $H/D = 4.5$ – 9 and the longitudinal spacing ratio of villus center $Z/D = 12.5$ – 22.5 . Then, the characteristics of the flocking drainage pipe in a two-dimensional flow field are analyzed with respect to the change in the ratio of the villus spacing at a low Reynolds number ($Re = 40$), hence providing a theoretical basis for the anti-crystallization technology in flocking drainage pipes.

2 Calculation model and research conditions

2.1 Governing equation

The Reynolds number refers to the number that characterizes the flow of fluid in one dimension, i.e.

$$Re = \frac{\rho u d}{\mu} \quad (1)$$

where ρ is the fluid density, in kg/m^3 ; u is the fluid velocity, in m/s ; d is the characteristic length of the bluff body, in m ; and μ is the hydrodynamic viscosity, in Pa s .

The inlet velocity of uniform fluid is $u = 0.02 \text{ m/s}$, the fluid density refers to $1,000 \text{ kg/m}^3$, the hydrodynamic viscosity is $1.00 \times 10^{-3} \text{ Pa s}$, and the diameter of the villus is 0.002 m . The Reynolds number $Re = 40$ is calculated based on equation (1). According to the result, it is within the range of laminar flow. Therefore, the compressibility of air and the three-dimensional flow field can be ignored. Instead, a two-dimensional model

can be used for calculations. The governing equations include continuity and Navier–Stokes equations, i.e.,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (2)$$

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (3)$$

$$\rho \frac{\partial v}{\partial t} + \rho u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \quad (4)$$

where ρ is the density, u and v are velocity components, t means time and p refers to pressure.

2.2 Calculation model

In the calculation model, the diameter D of the villus (cylinder) is 2 mm ; the length of the fluid area, 500 mm ; the width, 50 mm ; and the spacing between fluid inlet and villus, 125 mm . The horizontal spacing between the centers of villi is $4.5D$, $6.25D$ and $9D$, respectively, while the longitudinal spacing is $12.5D$, $17.5D$ and $22.5D$ respectively. The inlet boundary is on the left end. The outlet boundary, defined as the outflow boundary, is located at the right end. On the surface, the left and right boundaries along the flow direction and the villus (cylinder) are fixed without sliding (Figures 4–7).

3 Calculation results and analysis

3.1 Flow field distribution of villi in rectangular arrangement

The transverse spacing (H) between centers to villi in rectangular arrangement in the horizontal direction is $4.5D$, $6.25D$ and $9D$, respectively, and the spacing (Z)

Figure 4: Calculation model of villi in rectangular arrangement.

Figure 5: Calculation model of villi in staggered arrangement.

Figure 6: Grid model of villi in rectangular arrangement.

Figure 7: Grid model of villi in staggered arrangement.

from centers to the flow direction is $12.5D$, $17.5D$ and $22.5D$, respectively. The flow field distribution of drainage pipes with various spacings is shown in Figure 8. In each flow field figure, the dotted rectangular frame is selected for quantitative analysis. In Figure 8(a–c), from the upstream to the downstream, the velocity in the middle of the horizontal spacing of the first row of villi is mainly 0.020, 0.022, 0.024 and 0.022 m/s, respectively. With the increase in the longitudinal spacing Z , the flow wake at the downstream side of 0.022 m/s gradually becomes sharp. In Figure 8(d–f), from upstream to downstream, the velocity in the middle of the horizontal spacing of the first row of villi is basically 0.020, 0.022 and 0.020 m/s, respectively. With the increase in the longitudinal interval Z , the flow field of 0.022 m/s changes from “concave” to inverted trapezoid. According to Figure 8(g–i), the velocity in the middle of the

horizontal spacing of the first row of villi is mainly 0.020 m/s and that of the second row is mainly 0.020 m/s. As shown in Figure 8, with the increase in the horizontal spacing H , when $Z=12.5D$, $17.5D$ and $22.5D$, the velocity in the middle of the horizontal spacing of the first row of villi changes from 0.024 and 0.022 to 0.020 m/s.

This study aims to further analyze the groundwater flow field distribution around the villi in the flocking drainage pipes. Therefore, the villi in the middle of the first row are selected as the analysis object. Based on the analysis result, the flow field distribution is shown in Figure 9. In Figure 9(a), the horizontal direction of the cross arrow indicates the upstream and downstream status of the villi, and the vertical direction indicates the situation on the left and right sides. Figure 9(a–c) shows that the minimum velocity in the upstream and downstream of villi is 0.014 and 0.002 m/s, respectively; the maximum velocity of left and right sides of villi is 0.026 m/s, followed by 0.024 m/s. With the increase in longitudinal spacing Z , the distribution of upstream flow field is basically unchanged; the wake line of the downstream flow field changes from a rectangle to a triangle, with the tip of the wake gradually increasing. Figure 9(d) shows that the minimum velocity in the upstream and downstream of villi is 0.010 and 0.004 m/s, respectively; the maximum velocity on the left and right sides of villi is 0.026 m/s, followed by 0.024 and 0.022 m/s. Figure 9(e and f) shows that the minimum velocity in the upstream and downstream of the villi is 0.012 and 0.002 m/s, respectively; the maximum velocity on the left and right sides of the villi is 0.024 m/s, followed by 0.022 m/s. As shown in Figure 9(g–i), the minimum velocity in the upstream and downstream of the villi is 0.006 and 0.004 m/s, respectively; the maximum velocity on the left and right sides of the villi is 0.026 m/s and then 0.024, 0.022 and 0.020 m/s.

When the spacing is $H = 4.5D$ in the horizontal direction, with the increase in the longitudinal spacing Z , the minimum velocity in the upstream of the villi is 0.014 m/s, 30% lower than that of the inlet velocity; the minimum velocity in the downstream of the villi is 0.002 m/s, 90% lower than that of the inlet velocity; and

Figure 8: The flow field distribution of villi in rectangular arrangement: (a) $H = 4.5D/Z = 12.5D$, (b) $H = 4.5D/Z = 17.5D$, (c) $H = 4.5D/Z = 22.5D$, (d) $H = 6.25D/Z = 12.5D$, (e) $H = 6.25D/Z = 17.5D$, (f) $H = 6.25D/Z = 22.5D$, (g) $H = 9D/Z = 12.5D$, (h) $H = 9D/Z = 17.5D$, (i) $H = 9D/Z = 22.5D$.

the maximum velocity in the middle of two adjacent villi is 0.024 m/s, 20% higher than that of the inlet velocity. When the horizontal spacing is $H = 6.25D$, as the longitudinal spacing Z increases, the minimum velocity in the upstream of the villi is 0.012 m/s, 40% lower than that of the inlet velocity; the minimum velocity in the downstream of the villi is 0.002 m/s, 90% lower than that of the inlet velocity; and the maximum velocity in the middle of two adjacent villi is 0.022 m/s, 10% higher than that of the inlet velocity. When the horizontal spacing is $H = 9D$, as the longitudinal spacing Z widens, the minimum velocity in the upstream of the villi is 0.006 m/s, 70% lower than that of the inlet velocity; the minimum velocity in the downstream of the villi is 0.004 m/s, 80% lower than that of the inlet velocity; and the maximum velocity in the middle of two adjacent villi is 0.020 m/s, consistent with that of the inlet velocity.

At the longitudinal spacing $Z = 12.5D$, $17.5D$ and $22.5D$, as the horizontal spacing H increases, the minimum velocity in the upstream of the villi decreases from 0.014 to 0.006 m/s, 30–70% lower than the inlet velocity; the minimum velocity in the downstream of the villi increases from 0.002 to 0.004 m/s, 90–80% lower

than the inlet velocity; and the maximum velocity in the middle of two adjacent villi decreases from 0.024 to 0.020 m/s, 20–0% higher than the inlet velocity.

Based on the above analysis, it can be concluded that the increasing efficiency of velocity between adjacent villi is closely relevant to the horizontal spacing H of villi rather than the longitudinal spacing Z .

3.2 Flow field distribution of villi in staggered arrangement

The horizontal spacing (H) between centers to villi in staggered arrangement is $4.5D$, $6.25D$ and $9D$, respectively, and the spacing (Z) between centers and flow direction is $12.5D$, $17.5D$ and $22.5D$, respectively. The flow field distribution of drainage pipes with various spacings is shown in Figure 9. In Figure 10(a–c), from the upstream to the downstream, the velocity in the middle of the horizontal spacing of the first row of villi is mainly 0.020, 0.022, 0.024 and 0.022 m/s. With the increase in the longitudinal spacing Z , the flow wake at the

Figure 9: Flow field distribution around the villi in rectangular arrangement: (a) $H = 4.5D/Z = 12.5D$, (b) $H = 4.5D/Z = 17.5D$, (c) $H = 4.5D/Z = 22.5D$, (d) $H = 6.25D/Z = 12.5D$, (e) $H = 6.25D/Z = 17.5D$, (f) $H = 6.25D/Z = 22.5D$, (g) $H = 9D/Z = 12.5D$, (h) $H = 9D/Z = 17.5D$, (i) $H = 9D/Z = 22.5D$.

downstream side of 0.022 m/s gradually becomes sharp. In Figure 9(d–f), the velocity in the middle of the horizontal spacing of the first row of villi from upstream to downstream is mainly 0.020, 0.022 and 0.020 m/s, and the flow field of 0.022 m/s is mainly in the shape of “concave”. In Figure 9(g–i), the velocity in the middle of the horizontal spacing of the first row of villi is mainly 0.020 m/s and that in the middle of the second row is 0.018, 0.020, 0.022, 0.024 and 0.026 m/s. As shown in Figure 10, when $Z = 12.5D$, $17.5D$ and $22.5D$, as the horizontal spacing H widens, the velocity in the middle of the horizontal spacing of the first row of villi changes from 0.024 and 0.022 to 0.020 m/s.

In order to further analyze the groundwater flow field distribution around the villi in the flocking drainage pipes, the experiment selects the villi in the middle of the first row as the analysis object. Hence, the flow field distribution is shown in Figure 11. In Figure 11(a), the horizontal direction of the cross arrow indicates the upstream and downstream of the villi, and the vertical direction indicates the situation on the left and right sides. Figure 11(a) shows that the minimum velocity in the upstream and downstream of villi is 0.006

and 0.004 m/s, respectively; the maximum velocity of the left and right sides of villi is 0.028 m/s, followed by 0.026 and 0.024 m/s. Figure 11(b) shows that the minimum velocity in the upstream and downstream of villi is 0.014 and 0.004 m/s, respectively; the maximum velocity of the left and right sides of villi is 0.026 m/s and then 0.024 m/s. Figure 11(c) shows that the minimum velocity in the upstream and downstream of villi is 0.010 and 0.002 m/s, respectively; the maximum velocity of the left and right sides of villi is 0.026 m/s, followed by 0.024 m/s. Figure 11(d–f) shows that the minimum velocity in the upstream and downstream of the villi is 0.010 and 0.004 m/s, respectively; the maximum velocity in the left and right sides of the villi is 0.026 and 0.024 m/s, followed by 0.022 m/s. As it is shown in Figure 11(g–i), the minimum velocity in the upstream and downstream of the villi is 0.010 and 0.002 m/s, respectively; the maximum velocity on the left and right sides of the villi is 0.026, 0.024 and 0.022 m/s, followed by 0.020 m/s.

At the horizontal spacing $H = 4.5D$, as the longitudinal spacing Z widens, the minimum velocity in the upstream of the villi increases from 0.006 to 0.012 m/s

Figure 10: Flow field distribution of drainage pipelines in the villi in the rectangular arrangement: (a) $H = 4.5D/Z = 12.5D$, (b) $H = 4.5D/Z = 17.5D$, (c) $H = 4.5D/Z = 22.5D$, (d) $H = 6.25D/Z = 12.5D$, (e) $H = 6.25D/Z = 17.5D$, (f) $H = 6.25D/Z = 22.5D$, (g) $H = 9D/Z = 12.5D$, (h) $H = 9D/Z = 17.5D$, (i) $H = 9D/Z = 22.5D$.

and then decreases to 0.010 m/s, 70–30% lower than that of inlet velocity; the minimum velocity in the downstream of the villi decreases from 0.004 to 0.002 m/s, 80–90% lower than that of the inlet velocity; and the maximum velocity in the middle of two adjacent villi is 0.024 m/s, 20% higher than that of the inlet velocity. When the horizontal spacing is $H = 6.25D$, with the increase in the longitudinal spacing Z , the minimum velocity in the upstream of the villi is 0.010 m/s, 50% lower than that of the inlet velocity; the minimum velocity in the downstream of the villi is 0.004 m/s, 80% lower than that of the inlet velocity; and the maximum velocity in the middle of two adjacent villi is 0.022 m/s, 10% higher than that of the inlet velocity. When the horizontal spacing $H = 9D$, with the increase in the longitudinal spacing Z , the minimum velocity in the upstream of the villi is 0.010 m/s, 50% lower than that of the inlet velocity; the minimum velocity in the downstream of the villi is 0.002 m/s, 90% lower than that of the inlet velocity; and the maximum velocity in the middle of two adjacent villi is 0.020 m/s, consistent with the inlet velocity.

When the longitudinal spacing $Z = 12.5D$, with the increase in the horizontal spacing H , the minimum

velocity in the upstream of the villi increases from 0.006 to 0.010 m/s, which is 70–50% lower than that of the inlet velocity; the minimum velocity in the downstream of the villi decreases from 0.004 to 0.002 m/s, 90–80% lower than that of the inlet velocity; and the maximum velocity in the middle of two adjacent villi decreases from 0.024 to 0.020 m/s, 20–0% higher than that of the inlet velocity. At the longitudinal spacing $Z = 17.5D$, as the horizontal spacing H increases, the minimum velocity in the upstream of the villi decreases from 0.014 to 0.010 m/s, 30–50% lower than that of the inlet velocity; the minimum velocity in the downstream of the villi decreases from 0.004 to 0.002 m/s, 80–90% lower than that of the inlet velocity; and the maximum velocity in the middle of two adjacent villi decreases from 0.024 to 0.020 m/s, 20–0% higher than that of the inlet velocity. When the longitudinal spacing $Z = 22.5D$, with the increase in the horizontal spacing H , the minimum velocity in the upstream of the villi is 0.010 m/s, 50% lower than the inlet velocity; the minimum velocity in the downstream of the villi increases from 0.002 to 0.004 m/s and then decreases to 0.002 m/s, 80–90% lower than the inlet velocity; and the maximum velocity

Figure 11: Flow field distribution around the villi in the rectangular arrangement: (a) $H = 4.5D/Z = 12.5D$, (b) $H = 4.5D/Z = 17.5D$, (c) $H = 4.5D/Z = 22.5D$, (d) $H = 6.25D/Z = 12.5D$, (e) $H = 6.25D/Z = 17.5D$, (f) $H = 6.25D/Z = 22.5D$, (g) $H = 9D/Z = 12.5D$, (h) $H = 9D/Z = 17.5D$, (i) $H = 9D/Z = 22.5D$.

in the middle of two adjacent villi decreases from 0.024 to 0.020 m/s, 20–0% higher than that of the inlet velocity.

Based on the above analysis, it can be concluded that the increasing efficiency of velocity between adjacent villi is closely relevant to the horizontal spacing H of villi, instead of the longitudinal spacing Z .

In order to verify the flow field distribution and crystal distribution in the flocking drainage pipes, we compared the numerical simulation results with those from laboratory test results (flow rate 0.020 m/s). The results are shown in Figures 12 and 14 for the flow field of flocking drainage pipes with horizontal spacing

$H = 4.5D$ and longitudinal spacing $Z = 12.5D$. Figure 13 and 15 show the anti-crystallization test results for flocking drainage pipes [3].

Based on Figures 12–15, the flow velocity between the two horizontally adjacent villi along the longitudinal direction (0.024 m/s in the red part in the figure) is larger than that of the flow velocity at the inlet (0.020 m/s in the orange part in the figure), and the distribution of crystals at this position is the least. In a certain range on both sides of the villi, the velocity is the highest and the distribution of the corresponding crystal is the least; the velocity distribution in the upstream and downstream of the villi is also similar to that of the crystal, that is, more

Figure 12: Flow field distribution of flocking drainage pipe.

Figure 13: Crystal distribution in the flocking drainage pipes in the laboratory test.

Figure 14: Distribution of flow field around a single villus.

Figure 15: Distribution of crystals around villi in the laboratory test.

crystal will be located in the position with smaller velocity. It has been pointed out in previous studies [24–28] that the larger the flow velocity in the drainage pipe, the more difficult the crystallization is to be filtered and separated out, which conforms to the conclusions of this study.

4 Conclusions

Through the analysis of the numerical simulation results and comparison with the laboratory test results, the following conclusions are drawn:

(1) The increasing efficiency of flow velocity between adjacent villi in flocking drainage pipes is closely

related to the horizontal spacing H of villi rather than the longitudinal spacing Z .

- (2) Whether the villi are arranged in a rectangular or in a staggered manner, when the horizontal spacing H of villi is less than $6.25D$ (D refers to the diameter of the villus), the velocity in the middle of the adjacent villi increases by more than 10% compared with that of the inlet velocity; the minimum velocity in the upstream and downstream of villi decreases by 70% and 90%, respectively, compared with the inlet velocity.
- (3) The distribution of flow field in flocking drainage pipes is related to that of crystals in the laboratory test. More crystals can be found at the lower flow rate, while less can be found at the higher flow rate.

Acknowledgments: This work was supported by the Science and Technology Project of Guizhou Provincial Transportation and Department (No. 2017-123-011) and the Chongqing Municipal Education Commission Project (No. KJZH17120).

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