Study on Dynamic Pore Water Scouring of Asphalt Pavement by Mesoscopic Simulation Method

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Abstract: Dynamic water scouring caused by high-speed wheel load is an important cause of asphalt pavement water damage, which seriously affects the service life of asphalt pavement. In this paper, the dynamic water scouring simulation calculation model of asphalt pavement was established by mesoscopic level. Through the simulation model, the water scouring phenomenon of saturated and unsaturated pore in pavement caused by high-speed wheel load was discussed and studied, which mainly considered the influence of wheel speed, pore diameter, pore saturation state and other factors. The main conclusions are as follows: The water pressure, velocity and shear force in the pore are positively correlated with the wheel load velocity in both saturated and unsaturated states. The internal water pressure and fluid velocity of large pore are slightly lower than those of small pore, and the smaller the pore size is, the greater the vacuum negative pressure is. In the unsaturated state, the turbulent kinetic energy in the pore is an order of magnitude larger than that of saturated state, and the larger the pore is, the greater the turbulent kinetic energy is, so the water erosion damage of gas-liquid two-phase flowing is more serious than the saturated state.

1. Introduction

Dynamic water scouring is an important factor of asphalt pavement water damage. KAKAR[1] summarizes the reasons of asphalt film spalling as rupture, replacement, instantaneous emulsification, pore water pressure, dynamic water scouring and so on. Zhang Futian[2] studied the rule of dynamic water scouring accelerating water damage of asphalt mixture. Li Shaobo[3] calculated the theoretical value of dynamic water pressure under ideal state, and measured dynamic water pressure by electromagnetic fluid pressure sensor. The results show that the measured dynamic water pressure is proportional to the square of the wheel load velocity.

The current research on dynamic water scouring mainly focuses on the dynamic response of saturated asphalt pavement. This article attempts to establish a dynamic water scouring simulation calculation model from a mesoscopic level to discuss the phenomenon of pore dynamic water scouring caused by high-speed wheel loads in saturated and unsaturated conditions, which provides a basis for analyzing the mechanism of pore scouring of asphalt pavement and predicting the destruction process of asphalt pavement water erosion damage.

2 Dynamic pore water scouring in pavement under saturated condition

2.1 Calculation model and basic assumptions

The actual situation simulated by the saturated scour calculation model is that the pavement has large
pores due to cracks, looseness and other reasons, and the external precipitation causes more water in the pores. The pavement pore is approximately assumed to be saturated, without considering the influence of asphalt pavement deformation under vehicle load. The calculation model is set up with an inlet and an outlet. The initial pressure is applied at the inlet to simulate the high-speed wheel load to squeeze the road surface water into the inlet gap. The outlet is set as a zero-pressure outlet. The pore water produces isotropic turbulence under the action of wheel load. The standard \( k - \varepsilon \) model and the wall function method are used for simulation calculation. Enter the values of the pulsating kinetic energy \( k \) and the dispersion rate \( \varepsilon \) at the inlet. Figure 1 is the standard form of the calculation model.

The pore water pressure distribution, flow velocity, flow direction and viscous shear stress on the inner wall of asphalt pavement are calculated by using the steady state analysis module of finite element software FLUENT. The mechanism of pore scouring of asphalt pavement is analyzed through the distribution law of pressure field and flow field, and the failure process of water damage of asphalt pavement is predicted.

### 2.2 Effect of wheel load at different speeds

The pressure, velocity and shear force of water flow in the pores are related to the action speed of wheel load \(^4\). The standard pore model of 10 mm diameter is selected to calculate the influence of vehicle speed on each index. The initial conditions are applied as shown in table 1.

| Vehicle speed km/h | 20  | 40  | 60  | 80  | 100 | 120 |
|--------------------|-----|-----|-----|-----|-----|-----|
| Inlet pressure kPa  | 15.43 | 61.7 | 138.8 | 246.9 | 385.8 | 555.5 |
| Turbulent intensity | 5.4% | 5%  | 4.7% | 4.6% | 4.5% | 4.4% |
| Hydraulic radius mm | 1    | 1   | 1   | 1   | 1   | 1   |

The maximum dynamic water pressure of pavement caused by the measured vehicle speed of 80 km/h reaches 0.23 MPa, which is equivalent to the theoretical calculation value in Table 1, and confirms the correctness of the selection of inlet pressure of the calculation model to some extent. The calculation chart of 10mm pore model at 80km/h is given, as shown in figure 2.
According to the calculation cloud:

The position where the maximum static pressure appears in the calculation model is at the junction of the outlet gap and the lower side wall of the pore. Considering that the flow direction of the fluid is not completely parallel to the outlet gap, the flow velocity is large, and the fluid flow is hindered, so the fluid pressure energy is greater. The dynamic pressure is related to the velocity of the fluid. In the model, the dynamic pressure at the inlet and outlet is large, and the dynamic pressure at the connection position between the outlet and the pore reaches the maximum, where the water flow converges, the basin narrows and the flow velocity increases. The total outlet pressure is reduced by more than 60% compared to the total inlet pressure at all speeds. Viscous force will cause energy loss along the way, so the total pressure in the calculation domain is not conserved, which may also be one of the reasons for the attenuation of pore water pressure oscillation under pump suction. The turbulent kinetic energy reaches the maximum in the upper right corner of the model, that is, the small vortex range isolated from the entrance to the exit high-speed basin, where the change of fluid flow velocity is the most intense. The maximum viscous shear force occurs at the lower side of the outlet gap near the pore, and its value is related to the liquid flow rate.

According to the CFD numerical results, statistics of 10mm diameter pore standard model calculation index data as shown in table2.

Table 2 Summary of calculation results of saturation scour model at different speeds

| Vehicle speed (km/h) | 20   | 40   | 60   | 80   | 100  | 120  |
|---------------------|------|------|------|------|------|------|
| Max static pressure (kPa) | 10.28 | 41.39 | 93.03 | 165.7 | 258.9 | 373.8 |
| Max dynamic pressure (kPa)  | 6.64  | 27.58 | 63.81 | 115   | 181.2 | 261.4 |
| Average total pressure (kPa) | 9.28  | 37.17 | 83.74 | 149.6 | 234   | 336.1 |
| Inlet total pressure (kPa) | 15.43 | 61.73 | 138.8 | 246.9 | 385.8 | 555.5 |
| Total export pressure (kPa) | 5.45  | 22.6  | 52.2  | 94.3  | 148.6 | 214.1 |
| Max turbulent kinetic energy (m²/s²) | 0.64  | 2.6   | 5.81  | 10.74 | 16.7  | 23.6  |
| Max wall viscous shear force (Pa) | 90.9  | 329   | 671   | 1234  | 1877  | 2480  |
| Max flow rate (m/s) | 3.77  | 7.43  | 11.69 | 15.7  | 19.7  | 23.6  |

From Table 2, it can be seen that each calculated index is positively correlated with vehicle speed. Fitting the calculation results of the average total pressure in the pores at different vehicle speeds, the relationship between the average total pressure in the pores and the vehicle speed is obtained as shown in Figure 3(a). Fitting the calculation results of the maximum turbulent kinetic energy in the pores at different vehicle speeds, the relationship between the maximum turbulent kinetic energy in the pores and the vehicle speed is obtained as shown in Figure 3(b).

2.3 Effect of Pores with Different Diameters on Pore Water Pressure

The pore size of asphalt surface mixture is different and unevenly distributed due to the influence of gradation, compactness, long-term aging damage, scouring and cracks.[5] In order to explore the influence of pores of different sizes on the pavement scouring, the scouring calculations are carried out on the pore models of different sizes, and the summary results are shown in Table 3.
It can be seen from the data in the table:

Under the action of low-speed wheel load, the influence of pore diameter on pressure, flow velocity and shear force are small. Under the action of high-speed wheel load, the internal water pressure and fluid velocity of large-aperture pores are slightly lower than those of small-aperture pores; The maximum turbulent kinetic energy when the pore diameter 8mm, and the turbulent kinetic energy of the small pore is smaller. Compared with the low-speed wheel load, the high-speed wheel load can form a large vacuum negative pressure at the corner due to the high-speed vortex created in the pores, the smaller the pore diameter is, the greater the vacuum negative pressure is. The negative pressure reaches -23.2 kPa when the pore diameter is 4mm, and this negative pressure is related to the pore shape, pore outlet location, and inlet flow rate. Comparing the inlet pressure and the average total pressure in the pores, it is found that the average total pressure in the pores is about 50% less than that of the inlet pressure under both low speed and high-speed wheel load, which is related to the conditions considered in the simulation. The liquid flow in the pores is completely provided by the inlet pressure. Due to the effect of wall viscous shear force, energy loss along the flow path occurs in high-speed flow. The strength of the loss is related to the length of the flow, wall roughness, pore shape, outlet position and other factors. Because of the consistency of the calculation model, the strength of the loss is consistent at different speeds.

3 Dynamic pore water scouring in pavement under unsaturated condition

Due to the small diameter of the connected gap in asphalt mixture and the tension of liquid water itself, even if the road area water, many pores below will be unsaturated, but when the water flow is squeezed at high speed, it will quickly flow into unsaturated pores. Therefore, this section assumes that the road area is water, and the pores in the road are not yet saturated. The fluid in the calculation model is gas-liquid two-phase. This is a transient problem. It is a very short process for the wheel load to squeeze the road water into the void inside the road. The PISO algorithm in FLUENT software is selected to calculate the unsaturated scour model, the VOF model is selected to calculate the gas-liquid two-phase flow, and the standard $\kappa - \varepsilon$ model is selected to calculate the turbulence. The specific calculation process is improved on the basis of the standard model. The initial conditions of the gas-liquid two-phase calculation model are set in table 4.

| parameter                        | Low speed vehicle (20km/h) | High speed vehicle(100km/h) |
|----------------------------------|-----------------------------|-----------------------------|
| Min static pressure /kPa         | -0.1                        | -23.24                      |
| Max dynamic pressure /kPa        | 7.41                        | 204.7                       |
| Average total pressure /kPa      | 10.08                       | 258.4                       |
| Inlet total pressure /kPa        | 15.43                       | 385.8                       |
| Outlet total pressure /kPa       | 5.9                         | 164.6                       |
| Max turbulent kinetic energy/m²/s² | 0.536                   | 1.186                       |
| Wall viscous shear force /pa     | 90.6                        | 1748                        |
| Max flow velocity m/s            | 4.02                        | 21.3                        |

According to the calculation model, the calculation results of 6mm diameter unsaturated pore model at 100km speed are shown in table 5:

| initial condition | 20 | 40 | 60 | 80 | 100 | 120 |
|-------------------|----|----|----|----|-----|-----|
| inlet pressure /kPa | 15.4 | 61.7 | 138.8 | 246.9 | 385.8 | 555.5 |
| turbulent intensity /% | 5.4 | 4.7 | 4.6 | 4.5 | 4.4 |
| hydraulic radius /mm | 1 | 1 | 1 | 1 | 1 | 1 |
Table 5 Calculation results of unsaturated pore scouring by gas-liquid two-phase simulation

| time     | liquid distribution | static pressure distribution | streamline distribution |
|----------|---------------------|-----------------------------|-------------------------|
| 0.5ms    | ![Image](image1)    | ![Image](image2)            | ![Image](image3)        |
| 1ms      | ![Image](image4)    | ![Image](image5)            | ![Image](image6)        |
| 2ms      | ![Image](image7)    | ![Image](image8)            | ![Image](image9)        |

The calculation results of the maximum static pressure in the pores at different speeds are fitted, and the relationship between the maximum static pressure in the pores and the speed is shown in Fig. 4 (a). The relationship between the maximum turbulent kinetic energy and the vehicle speed in the pores is obtained by fitting the calculation results of the maximum turbulent kinetic energy in the pores at different speeds, as shown in Fig. 4 (b).

![Image](image10) ![Image](image11)

Fig 4 Fitting curve of unsaturated scouring calculation and vehicle speed

It can be seen from the fitting results that the pore water pressure and the maximum turbulent kinetic energy are positively correlated with the vehicle speed, which is consistent with the change law of the saturation calculation results.

4. Comparison of dynamic water scouring under saturated and unsaturated conditions

In order to compare the difference of dynamic water scouring characteristics between saturated state and unsaturated state in pores, two pore models with different diameters are set up under the speed of 100km/h. The saturated state is calculated by steady state and the unsaturated state is calculated by solid state. The results are shown in Table 6.

Table 6 Comparison of simulation results of saturated and gas-liquid two-phase conditions

| pore diameter /mm | max static pressure /kPa | Max negative pressure /kPa | Max dynamic pressure/kPa | Max turbulent kinetic energy m²/s² |
|------------------|---------------------------|---------------------------|--------------------------|-----------------------------------|
|                  | Saturated unsaturated    | Saturated unsaturated    | Saturated unsaturated    | Saturated unsaturated             |
| 4                | 272                       | 314                       | -23                      | -79                               | 204                              | 232                              | 11.86                           | 10.9                            |
| 6                | 267                       | 298                       | -14                      | -92                               | 201                              | 240                              | 18.02                           | 88                              |
| 8                | 257                       | 291                       | -15                      | -78                               | 194                              | 228                              | 18.7                            | 99.2                            |
| 10               | 258                       | 313                       | -11                      | -22                               | 181                              | 247                              | 16.7                            | 143.6                           |
The calculation results show that each index in the transient calculation changes dynamically with time. The maximum flow velocity, maximum static pressure, maximum dynamic pressure and maximum negative pressure of the unsaturated model exceed the saturated model after the calculation reaches equilibrium, and the occurrence position is basically the same as that of the saturated model. The maximum negative pressure is at the corner of the outlet gap, and the maximum positive pressure is at the junction of the lower wall and the outlet gap. It can be seen that the shape of the model, especially the position of the inlet and outlet, has a great influence on the state of dynamic water scouring. The absolute value of positive and negative pressure at the corner of the pore in the gas-liquid two-phase flow state is larger than that of the satiated case, especially the small area of the vacuum negative pressure zone formed at the corner of the exit gap, the unsaturated calculation result is 2-6 times larger than that of the satiated model, which will increase the damage of the dynamic water scouring on the location of the mixture and slurry film, gradually leading to the pore exit location with repeated scouring gradually expand. Similarly, the turbulent kinetic energy in the pore is an order of magnitude larger than that in the saturated case due to the existence of gas, and the larger the pore is, the greater the turbulent kinetic energy is. Therefore, it can be speculated that the gas-liquid two-phase flow is faster than the saturated scouring damage.

5. Conclusion

At present, the research on dynamic water scouring mainly focuses on the dynamic response of saturated asphalt pavement. This paper studies the characteristics of saturated and unsaturated pore water scouring caused by high-speed wheel load through simulation calculation, which is of great significance to reveal the mechanism of water damage of asphalt pavement. The conclusions are as follows:

1) The water pressure, velocity and shear force in the pore are positively correlated with the wheel load velocity in both saturated and unsaturated states.

2) The shape of pore, especially the position of inlet and outlet, has a great influence on the state of dynamic water scouring. The total pressure of outlet at each speed decreases by more than 60 % compared with the total pressure of inlet, and the average total pressure in pore is about 50 % lower than that of inlet. The internal water pressure and flow velocity of large pores are slightly lower than those of small pores, but the smaller the pore size is, the greater the vacuum negative pressure is.

3) The turbulent kinetic energy in the pores of gas-liquid two-phase flow is an order of magnitude larger than that in the saturated situation due to the existence of gas, and the larger the pores are, the greater the turbulent kinetic energy is. In summary, gas-liquid two-phase flow has faster scouring damage than saturated flow.

References

[1] KAKAR M R, HAMZAH M O, VALENTIN J. A review on moisture damages of hot and warm mix asphalt and related investigations[J]. Journal of Cleaner Production, 2015, 99: 39-58.
[2] Zhang Futian, Gao Junqi, Lu Hongqiang. Study on water damage law of asphalt mixture accelerated by dynamic water scouring [J]. Journal of Hefei University of Technology (Natural Science Edition), 2021, 44 (06): 790-793.
[3] Li Shaobo, Zhang Hongchao, Sun Lijun. Formation and simulation measurement of hydrodynamic pressure [J]. Journal of Tongji University (Natural Science Edition), 2007 (07): 915 – 918.
[4] Dong Zejiao, Cao Liping, Tan Yiqiu. Spatial distribution analysis of dynamic response of saturated asphalt pavement [J]. Civil Engineering and Environmental Engineering, 2007, 29 (004 ) : 79.
[5] Cai Yanxia, Shen Aiqin, Guo Yinchuan, Wang Deqiang. Dynamic water damage behavior and dynamic seepage test simulation of asphalt mixture [J]. Journal of Chang 'an University (Natural Science Edition), 2015,35 (02): 13-18 + 25.