

Simulation study on surface dynamic water pressure of bridge deck pavement

Mingzhi Sun^{1*}, Xiong Tang¹, Jing Xu²

¹Research Institute of Highway Ministry of Transport, Beijing 100088

²School of transportation, Southeast University, Nanjing 211189

The corresponding author's e-mail address is mz.sun@rioh.cn

Abstract The dynamic water pressure will be caused at the surface of the bridge deck pavement when high-speed wheel load drive through. On the one hand, it can reduce the anti-sliding performance of the surfacing layer which is not conducive to traffic safety, on the other hand, dynamic water pressure will continuously scour pavement material and degrade the material performance. In order to explore the formation and evolution laws of dynamic water pressure on the pavement surface, analysis the factors influence on dynamic water pressure, the finite element method was used to establish the simulation calculation model, and the influence factors such as the water film thickness, different speed of wheel load and tire pattern depth were considered. The main conclusions are as follows: The finite element method to calculate the tire ground area and the vertical displacement can give reasonable geometry size of the tire in the computational fluid domain; the wheel drives through at high speed to squeeze the water at the surface. The tire pattern cannot discharge the water under the tire quickly, and most of the water that is stuck in the grounding area forms the dynamic water pressure. The value of the dynamic water pressure is positively correlated with the wheel load speed and the water film thickness. When the speed is 100km/h, the maximum dynamic water pressure is about 0.272MPa.

1. Introduction

Bridge deck pavement will be covered with a certain thickness of water film when the water cannot discharge in time on a rainy day. The surface water pressure will be caused by high speed wheel load. On the one hand, surface water pressure can reduce the anti-sliding performance of the surfacing layer, and it is not conducive to traffic safety. On the other hand, dynamic water pressure will continue to scour pavement materials, and the material performance will gradually reduce. Therefore, the research on the formation and development characteristics of dynamic water pressure is of great significance to design more secure, efficient, green pavement structure, and develop better anti-scouring and water damage resistance pavement materials.

At present, there are two kinds of methods for the research of surface dynamic water pressure which respectively are theoretical calculation and field measurement [1-4]. Li [5] obtained the calculation value of the surface dynamic water pressure by using Bernoulli's law under the ideal state, and the existence of the dynamic water pressure was verified through the field measurement. Gao [6] designed a fiber optic sensor which can measure the dynamic water pressure of the road surface by using the fiber grating sensing principle, and the measured water pressure at the speed of 80km/h can reach to 0.23Mpa. But theoretical calculation method often does a lot of assumptions, like it is difficult to consider the influence of the tires pattern on water pressure. Meanwhile due to the influence of such



factors as instrument and embedment method, the error of test value by the field measurement method is generally large.

Rely on the powerful calculation power of the computer, numerical simulation technology can well consider the influence of many complex factors, and the calculation results can achieve good accuracy and stability. Therefore, this article adopts the method of numerical simulation, establish dynamic water pressure finite model caused by wheel load passing the bridge deck pavement. The generation process of dynamic water pressure at road surface was analyzed, and the influence of the water film thickness, speed of wheel load, tire tread depth on the dynamic water pressure value was also researched.

2. Calculation of vertical displacement and grounding area after tire deformation

In order to accurately establish the simulation model of the interaction between tire and road surface water, it is necessary to determine the specific driving state of the tire in the fluid field. Therefore, ABAQUS finite element software is used in this section to establish the interaction model between tire and road surface. The purpose is to determine the vertical displacement after tire deformation and the ground area of the tire.

2.1 Boundary conditions

In the tire model, the contact of the tire rim and rim is simplified as the fixed constraint of the node. The master constraint is the downward displacement of the center point of the tire, and the slave constraint is downward displacement of the nodal set in the contact point of the rim and the tire circle.

The base and side of the paving layer are set to fixed constraints. Here the rim is assumed to be rigid. The nonlinear boundary conditions of the tire can be reflected in the contact between the tire and the bridge and the contact boundary between the tire and the rim. For the contact between the tire and the steel deck pavement, the constraint function method is used to set the contact constraint when the friction coefficient between the tire and the road surface is not considered.

2.2 Material parameters

The thickness of epoxy asphalt pavement is 50mm, the modulus is 1000MPa, and poisson ratio is 0.25.

The density of the standard rim is 2700kg/m³, the elastic modulus is 100GPa and poisson ratio is 0.3.

The tire size is 10.00R20, the radian height is 5.5mm, the width of the driving surface is 214mm, the width of the section is 278mm, and the outer diameter of the tire is 1052.5mm.

2.3 Tire - steel bridge deck model.

The model of tire - steel bridge deck was set up as shown in Figure 1. The Full Newton iteration method is used to solve the problem, and the time function is adjusted according to the convergence condition. The 25 KN concentrated load was applied in the center of the rim. The method of implicit was used for the calculation, the time step was set to twenty steps, the maximum iterations is 15 for each step, and the minimum iterations is 0. The convergence is judged based on residual error checking, and the relative residual take 0.1.

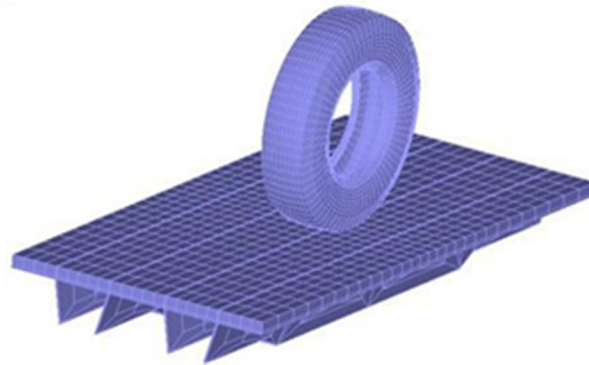


Figure 1 Tire - steel bridge deck model

2.4 Analysis of calculation results

After calculation, the vertical displacement diagram of the tire is obtained as shown in Figure 2, and the ground area of tire is shown in Figure 3.

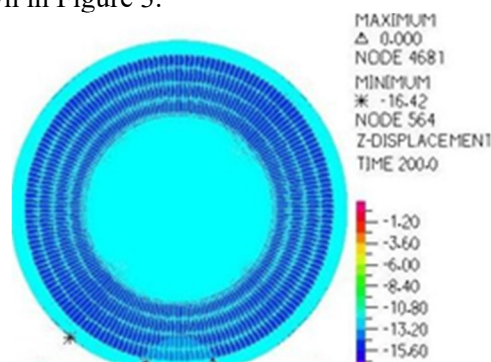


Figure 2 The vertical displacement diagram of the tire



Figure 3 The ground area of tire

It is calculated that the maximum deformation of the tire was 16.42mm and the ground area of the tire was approximately 391.60 cm².

3 Simulation of surface dynamic water pressure on deck pavement

3.1 Calculation assuming

After the ground pressure of tire is evenly distributed, the tire driving on the water surface can be regarded as the road surface and the uniform thickness of the water film impact the tread surface at a certain speed. Therefore, tire is seen as reference, it is assumed that air and water move towards the tire in a certain velocity. This method can simulate the motion of the tire on the pavement surface with water film. The key point of the simulation is to obtain the distribution of dynamic water pressure when water impact on the tire.

3.2 Model establish

1) Range of model

The area which is relevant to the calculation should be considered when modeling. Because the model is just part of the whole, it should also pay attention to that the boundary conditions of the model must be reasonable and accurate to simulate the flow state of whole space. If the flow field is backflow, the calculation area should be increased, but the model calculation area should not be too large so as to avoid the complexity of calculation. After repeated trial and error, the calculation range of the flow field model was determined as: 800mm in length, 600mm in width and 40mm in height.

2) Calculation domain of fluid model

The geometrical appearance size of the fluid model with the action of pneumatic tire is calculated according to the vertical displacement and ground area calculated by the tire grounding model in the previous section. The pre-processing software GAMBIT was used to obtain the fluid domain by performing Boolean operation on the fluid model as shown in Figure 4. The model is two-phase flow, the upper air thickness is 32mm and the lower water film thickness is 8mm.

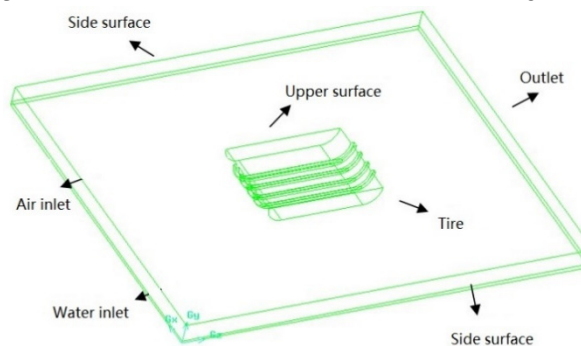


Figure 4 Fluid domain calculation model

3) Boundary conditions and initial conditions

The inlet velocity of air and water at the front end of the fluid domain model is 22.22m/s which simulates the speed of 80km/h driving on the surface of the steel deck pavement. The base of model is set to movable wall. Its speed matches the speed of air and water. The rear and surface of model is set to pressure outlet. The side of the model is set to the absolutely smooth wall.

The model needs to be initialized with the flow field namely to give the initial value of the flow field, including pressure, speed and temperature. The initial pressure of the model is 0.101MPa which is equal to atmospheric pressure, and the initial inlet velocity is 22.22m/s, and the initial temperature is at room temperature of 25°C.

Because the computational domain is gas-liquid two-phase flow, the VOF model is used to simulate the dynamic water pressure generated by the tire.

3.3 Analysis of dynamic water pressure simulation results

1) Generating reason of dynamic water pressure

After calculation, the dynamic water pressure contour was obtained when the vehicle speed is 80 km/h as shown in Figure 5. The maximum dynamic water pressure on the deck pavement surface is generated at the center position of the frontend of tire, and the value can reach to 0.213MPa.

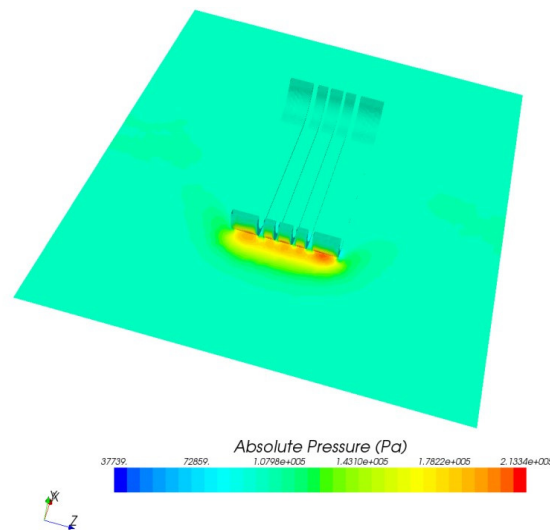


Figure 5 Dynamic water pressure contour of deck pavement surface

The velocity distribution contour of water film on steel bridge deck pavement under the load of tire is shown in Figure 6.

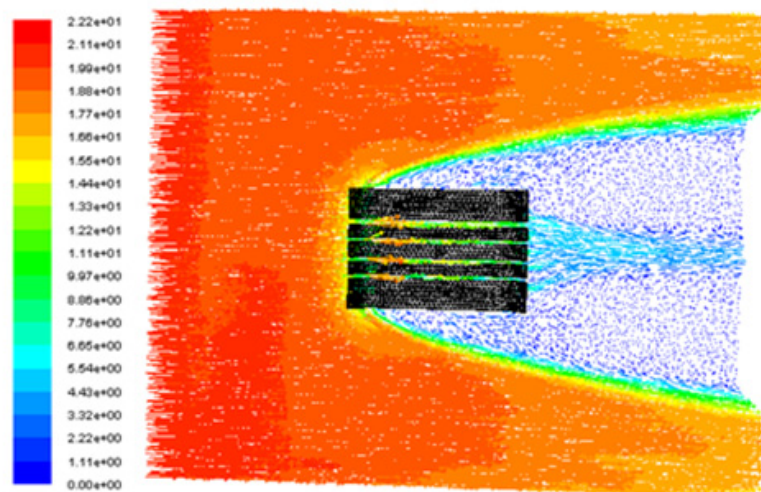


Figure 6 Velocity distribution contour of surface water film

As is shown in Figure 6, there is large amount of water with high flowing velocity at the front of tire, while only small amount of water is discharged at the back end of the tire at a speed of about 2m/s. This suggests that for high speed vehicle, water flowing into the tire ground area is beyond the drainage capacity of tire pattern, only a small amount of water can be discharged through the tire longitudinal pattern, a large amount of water appear stranded in front of the tire, then the dynamic water pressure form.

2) The influence of vehicle speed on dynamic water pressure

Vehicle speed respectively 40km/h, 60km/h, 80km/h and 100km/h (The corresponding inlet velocity of water and air is respectively 11.11m/s, 16.67m/s, 22.22m/s and 27.78m/s) was selected to research the influence on the dynamic water pressure of steel bridge deck. For the four working conditions, the maximum dynamic water pressure under each working condition is extracted, and the relation between maximum dynamic water pressure and the driving speed of the vehicle is shown in Figure 7.

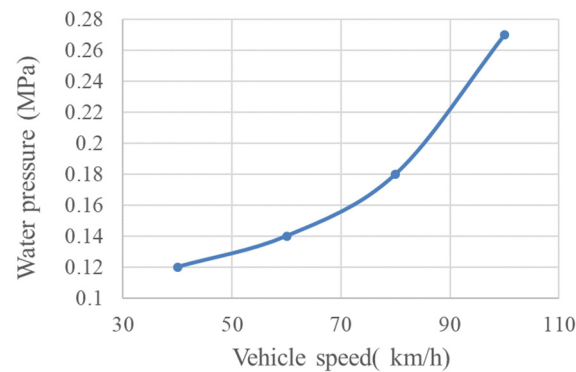


Figure 7 The relation between maximum dynamic water pressure and vehicle speed

As shown in the Figure 7, the maximum water pressure is positively correlated with vehicle speed. When the speed is 100km/h, the maximum dynamic water pressure can reach 0.272MPa which increases by 126% compared with the speed of 40km/h. Therefore under the condition of that water skiing phenomenon not produce, the higher the vehicle speed is, the greater the dynamic water pressure value at the bottom of tire is. The dynamic water pressure produced by the high speed is 2~3 times of the value produced by low speed.

3) The influence of water film on dynamic water pressure

The water film thickness is taken respectively 3mm, 5mm, 8mm and 10mm at the steel bridge deck pavement surface. The depth of tire pattern is set as 8 mm. The influence of water film thickness on dynamic water pressure was researched at different speed as shown in Figure 8.

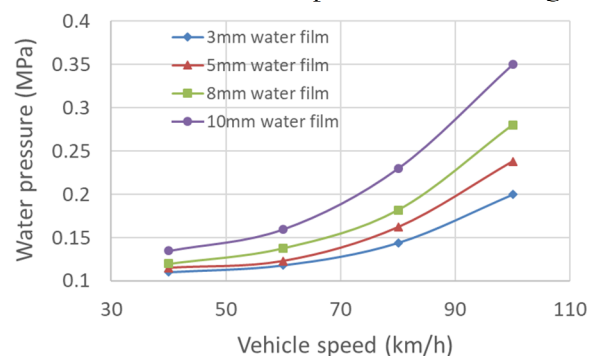


Figure 8 The maximum water pressure of different water film thickness

As shown in Fig.8, the dynamic water pressure of pavement surface increases with the increase of water film thickness, and the increase trend of dynamic water pressure under different water film thickness is basically consistent.

When the water film thickness is 10mm, the dynamic water pressure is obviously greater than that of other water film thickness. When tire pattern depth is 8mm and the water film thickness is 10mm, water film thickness is greater than the tire pattern depth, the drainage capacity is obviously inadequate, this lead to more water concentrated in the front tire and bigger dynamic water pressure generates. Therefore, in the case that the vehicle does not produce water skiing phenomenon, the higher the water film thickness is, the greater the dynamic water pressure will be.

The maximum dynamic water pressure generated in these conditions that the water film thickness is 10mm, the depth of tire pattern is 8mm and the driving speed is 100km/h. The maximum dynamic water pressure can achieve 0.349MPa. The minimum dynamic water pressure generates in the working conditions that water film thickness is 3mm and the driving speed is 40km/h. The minimum dynamic water pressure is 0.109MPa.

4) The influence of tire pattern depth on dynamic water pressure

With the increase of tire wear, the tire pattern depth will become smaller and smaller, and the adhesion with the road surface will decrease which will cause the tire to slide on water. The model in previous section is no wear tire condition (tire pattern depth is 8 mm).

In order to better understand the dynamic water pressure of steel bridge deck pavement surface, the worn tire model was established (tire pattern depth is 5mm and 3mm respectively) to study the dynamic water pressure of the steel bridge deck under conditions of different tire pattern depth.

When the water film thickness is 8mm and the tire pattern is 8mm, 5mm and 3mm respectively, the dynamic water pressure of the deck pavement surface is shown in Figure 9.

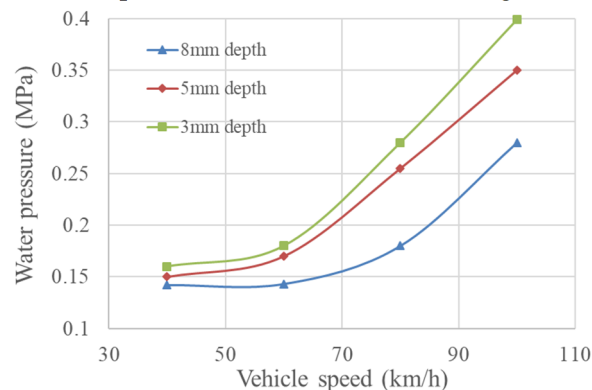


Figure 9 The maximum dynamic water pressure of different tire pattern depth

As shown in Figure 9, the maximum dynamic water pressure increased with the decrease of tire pattern depth, and when the tread depth is 8mm, the dynamic water pressure value is significantly smaller than the other two working conditions. The reason may be that the thickness of the water film is 8mm, and the tire pattern depth is also 8mm, which can better discharge the water through the longitudinal pattern. When the depth is 5mm, the drainage effect of longitudinal pattern is still obvious. However, when the depth of tire pattern is 3mm, the value of dynamic water pressure increases significantly, this indicates that the longitudinal pattern has been disqualified for drainage. Therefore, the increase of tire pattern wear is not good for drainage, and the value of dynamic water pressure is greater than that of new tire.

From what has been discussed above, the increase of driving speed, the increase of water film thickness and the decrease of the tire pattern depth will increase the dynamic water pressure of steel bridge deck pavement surface. When driving speed is 100km/h, water film thickness is 10mm and tire pattern depth is 3mm of the most unfavorable condition, the maximum dynamic water pressure of epoxy asphalt pavement for steel bridge deck surface can reach to 0.399MPa.

4. Conclusions

1) The tire model is established by analyzing the boundary conditions between the tire and pavement to obtain the vertical displacement of the tire and the ground area when the inflation is finished. Then the computational domain of the dynamic water pressure fluid model is determined according to the calculation results of the tire ground model.

2) The dynamic water pressure value under different working conditions was calculated by changing the inlet velocity of air and water, the water film thickness and tire tread depth. The results show that the speed increase, water film thickness increase, tire tread depth decrease will cause the increase of dynamic water pressure on the steel bridge deck pavement surface.

3) The CFD model under the most unfavorable condition was established, and the maximum dynamic water pressure value produced on steel bridge pavement surface was 0.399MPa without water skiing.

Acknowledgements

The research work described herein was funded by the Fundamental Research Funds for the Central research institutes (RIOH 2016-9020). This financial support is gratefully acknowledged.

References

- [1] Zhou C H, Chen J Y, Wang Z R, et al, 2008. Dynamic numerical method of pore water pressure and its influence parameters for asphalt pavement. *Journal of Central South University*, chapter 11 volume 87 pp 1615–1618.
- [2] Zhou C, Wang Z, Chen J, et al, 2015. Numerical Computation and Analysis on Dynamic Pore Water Pressure in Asphalt Pavement. *International Conference on Transportation Engineering*, pp 2981-2986.
- [3] Jiang W, Zhang X, Zhi L I, 2011. Simulation Test of Dynamic Water Pressure for Asphalt Pavement. *Journal of Highway & Transportation Research & Development*, chapter 6 volume 28 pp 877-872.
- [4] Gao J, Guo C, Liu Y, 2015. Measurement of pore water pressure in asphalt pavement and its effects on permeability. *Measurement*, chapter 4 volume 62 pp 81-87.
- [5] Li S, Zhang H, Sun L, 2007. Development and Simulation Measurement of Dynamic Hydraulic Pressure. *Journal of Tongji University (Nature science)*, chapter 7 volume 35 pp 915-918.
- [6] Gao J, Chen H, Ji T J, 2009. Study of dynamic hydraulic pressure measurement on asphalt pavement using optical fiber sensing. *Transducer and Microsystem Technologies*, chapter 9 volume 28 pp 59-61.