

Numerical Simulation of Drainage Process for Sand Cushion in Saturated Asphalt Pavement

Yue Jiannan

*Postgraduate in Geotechnical Engineering
School of Civil Engineering and Architecture, Southwest Petroleum University
Chengdu, China
e-mail: 29985635@qq.com*

Liu Jianjun^{1,2}

Professor

*1: School of Civil Engineering and Architecture, Southwest Petroleum University,
Chengdu, China;*

*2: State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation
(Southwest Petroleum University), Chengdu, China
e-mail: liujj0906@163.com*

ABSTRACT

Drainage has important influence for long-term stability and service life of the pavement. With a lot of researches, it is found that the damage of pavement structure is exacerbated with rainfall or groundwater flowing into the pavement and a repeated traffic load. Pavement structure is divided into surface course, base and cushion. Cushion has good drainage properties and is conducive to the discharge of the free water inside the pavement structure. In this paper, the fluid-solid coupling mathematical model under the condition of saturation has been built based on the effective stress principle, Darcy law and the Biot theory. A three-dimensional numerical model has been established with the finite element software ABAQUS. With the calculation of drainage consolidation process of saturated sand cushion under rolling load, it can provide reference for engineering. The calculation results show that the drainage time and the drainage effect are influenced by rolling load and void ratio. The rate of change of the pore pressure and void ratio is different in the central and the edge of the road. The pore pressure distribution and void ratio are banded and symmetrical.

KEYWORDS: Saturated asphalt pavement; sand cushion; fluid-solid coupling; numerical simulation

INTRODUCTION

There is close relationship between the strength and stability of pavement and the water. Water is one of the main factors among the various diseases in pavement. The strength of asphalt pavement materials could be reduced by the water. With the long-term effects of rolling load, the road damage is exacerbated as well as the decline of mechanical properties and service performance of the pavement structure. In road construction, the pavement is layered construction. The water in top of the base is channeled and insulated by cushion. And the stress from the pavement is also diffused by cushion. Therefore, the researches on drainage process for cushion have a great significance. At present, the researches on the problems of drainage always focus on the loss of pavement structure strength. There are few researches on pavement seepage process. Zhao Hongduo, *et al.*^[1], have carried out simulation analysis on the infiltration laws of highway median and the influence of the roadbed and pavement in the different conditions of width, rainfall intensity and rainfall duration using VS2DI. Zhao Jiang^[2] have carried out simulation analysis on the distribution and variation of seepage flow field in the conditions of various different waterproof and drainage project, four different rainfall intensity and different rainfall duration using SEEP/W. Ariza^[3] have simulated on unsaturated seepage for The three highways In the state of Minnesota based on the theory of unsaturated soils using SEEP/W. Mahboub^{[4][5]} have carried out steady seepage analysis on the cement concrete asphalt overlay using SEEP/W. Stormont^[6] have carried out simulation on the seepage flow field of typical pavement structure based on the theory of unsaturated soils using VS2DHI. The above researches have important significance on pavement drainage analysis. However, most attention have focused on the pavement seepage analysis in the effect of rainfall without the consideration of the change of the flow field in the rolling load. There are too many two-dimension analysis and little consideration on fluid-solid coupling effect. In fact, free water flow into the pavement with the effect of rainfall. There is a fluid-solid coupling process in pavement drainage process under vehicle loads. In this paper, combined with the effective stress principle, Darcy law and the Biot theory, coupled mathematical model of seepage flow has been established. On that basis, three-dimensional numerical model has been established depending on the use of Abaqus finite element software. The drainage process of the saturated sand cushion in the ideal condition and compaction effect has been simulated, which could provide the reference for the engineering construction.

NUMERICAL CALCULATION THEORY

The actual asphalt pavement structure not only has layered characteristics on vertical but also has the characteristics of porous media. Therefore, the pavement can be viewed as the composite elastomeric which has four structural layers in the thickness direction and different material. Calculation has been carried out on a section of the road. And make the following hypotheses:

(1) Each construction layer is a continuous, homogeneous, isotropic elastic material and obeys Hooke's law;

(2) The load which is imposed on the upper surface of the elastic layer system is viewed as the axially symmetric load;

(3) Each layer is completely continuous;

(4) Each layer is in uniform compaction state. The materials of base and cushion are fully saturated and the porosity distribution is uniform;

(5) The seepage in the pavement structure obeys Darcy law and the fluid is incompressible;

(6) All pressure would be carried by pore water when the load is applied;

Based on the assumptions above, effective stress principle could distinguish the stress carried on soil particle skeleton and pore water and consider the coupling effect of soil skeleton deformation and pore water pressure dissipation, which is more in line with the actual situations. According to the effective stress principle of saturated soil, we know that:

$$P = \sigma A - \mu A_w \quad (1)$$

where P is the resultant force of the contact force between particles on section in the vertical direction; μ is pore water pressure; A is section area of the soil; A_w is the corresponding area of pore water on section.

According to the Darcy law, water seepage flow in unit time through the porous media is inversely proportional to the length of seepage path and is proportional to discharge section area and total water head loss. The expression can be expressed as:

$$Q = KFh/L \quad (2)$$

where Q is seepage flow in unit time; F is flowing section; h is total water head loss; L is the length of seepage path; $I = h/L$ is hydraulic slope; K is permeability coefficient.

In the Biot theory, soil skeleton is assumed to be linear elastic and line with small deformation theory. And the seepage is in line with Darcy law. Fluid in soil particles and pore is incompressible and deformation is produced by pore compressibility.

According to the effective stress principle, three-dimensional equilibrium equations on road construction are as follows:

$$\begin{aligned} \frac{\partial \sigma'_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} - \frac{\partial p}{\partial x} &= 0 \\ \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma'_y}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} - \frac{\partial p}{\partial y} &= 0 \\ \frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma'_z}{\partial z} - \frac{\partial p}{\partial z} &= -\gamma \end{aligned} \quad (3)$$

where γ is soil density; σ_x , σ_y , σ_z is normal stress; τ_{xy} , τ_{yz} , τ_{zx} is shear stress; p is pore pressure.

Hypothesis has been established that cushion layer soil is elastic material. The constitutive equations can be expressed as :

$$\sigma'_{ij} = D_e \varepsilon_{ij} \quad i, j = 1, 2, 3 \quad (4)$$

where σ'_{ij} is effective stress; D_e is elasticity matrix; ε_{ij} is strain.

Deformation geometric equations of road structure are as follow:

$$\begin{aligned} \varepsilon_x &= -\frac{\partial u}{\partial x}, \gamma_{yz} = -\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right) \\ \varepsilon_y &= -\frac{\partial v}{\partial y}, \gamma_{zx} = -\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right) \\ \varepsilon_z &= -\frac{\partial w}{\partial z}, \gamma_{xy} = -\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) \end{aligned} \quad (5)$$

where u , v , w is displacement respectively of the x , y , z direction.

Considering the compressibility of the road structure, mathematical model of seepage field in the stress is as follow [Li Peichao]:

$$-\nabla \cdot \left(\frac{k}{\mu} (\nabla p - \rho_f g \nabla D) \right) + \frac{\partial \varepsilon_v}{\partial t} + \left(\frac{1-\varphi}{K_s} + \frac{\varphi}{K_f} \right) \frac{\partial p}{\partial t} = 0 \quad (6)$$

where k is absolute permeability of porous media; μ is fluid viscosity; p is fluid pressure; ρ_f is fluid density; $\varepsilon_v = \varepsilon_x + \varepsilon_y + \varepsilon_z$ is volumetric strain; t is time; φ is void ratio; K_s is the volume elastic compression modulus; K_f is the volume elastic compression modulus of fluid.

When seepage and stress coupling constitutive relationship is established, strain is the coupling objects. Therefore, the combined effect of the effective stress and the mechanical properties of porous media have been implied into coupling constitutive relationship. Thus the coupling relationship of seepage and stress can be expressed as:

$$\varphi = \frac{1}{1 + \varepsilon_v} (\varphi_0 + \varepsilon_v) \quad (7)$$

$$K = K_0 \frac{\left(1 + \frac{\varepsilon_v}{\varphi_0}\right)^3}{1 + \varepsilon_v} \quad (8)$$

where $\varepsilon_v = \varepsilon_x + \varepsilon_y + \varepsilon_z$ is volumetric strain; φ_0 is void ratio when the effective pressure is zero; K_0 is permeability when the effective pressure is zero.

NUMERICAL MODELS

Based on the assumptions above, the drainage consolidation process of asphalt highway pavement sand cushion in the rolling load has been simulated with transient analysis function in ABAQUS finite element software. The specifications of the numerical model are $16 \text{ m} \times 22 \text{ m} \times 5.95 \text{ m}$ and cross-section is divided into four layers. In addition there is two-way 1% of transverse slope on surface. The longitudinal gully has been set outside the cushion. The thickness of each layer from top to bottom is respectively: the thickness of asphalt concrete pavement is 0.15 m; the thickness of asphalt macadam base is 0.5m; the thickness of sand cushion is 0.3m and the thickness of clay roadbed is 5.0m.

The elastic constitutive model has been used into each pavement structure layer. Base and cushion have been simulated as saturated porous media. The parameters of pavement structural mechanics are shown in Table 1.

Table 1: Calculation parameters of each layer in road structure

| structural layer | Young modulus E(MPa) | Poisson's ratio | Permeability(m/s) |
|------------------|----------------------|-----------------|-------------------|
| surface | 1400 | 0.30 | - |
| base | 1500 | 0.25 | 1E-7 |
| cushion | 1300 | 0.35 | 1E-6 |
| roadbed | 200 | 0.30 | - |

In this paper, base and cushion under the condition of saturation have been simulated. Cushion has good drainage properties. Free water in base is discharged through the cushion. First, the drainage process under the conditions of different pore ratio has been simulated with the same load. When rolling load is 150kPa, void ratio is 0.15 and k is 2E-7 m/s; void ratio is 0.25 and k is 6E-7 m/s and void ratio is 0.35 and k is 1E-6 m/s. In addition, drainage process has been considered in the same void ratio and different rolling load. In the initial analysis step, the bottom surface of the model is impervious surface. The displacement of the bottom surface in all directions is constrained. Meanwhile the displacement of the side face in the vertical direction is not constrained, but in the other directions is constrained. In the consolidation analysis step, the side face of the cushion is set to be permeable surface along the route direction (the simulation of vertical gullies) with impervious surface on cross-section.

In the load analysis step, uniformly distributed pressure has been once applied on pavement. In the first condition, rolling load is 150kPa. In the second condition, rolling load is 50kPa, 150kPa and 250kPa respectively. In this example three-dimensional drainage consolidation process in saturated pavement sand cushion has been simulated. The pore pressure element is C3D8P with 8 nodes which have been used for base and cushion. Solid element has been used for other structural layers. The mesh is shown in Figure 1.

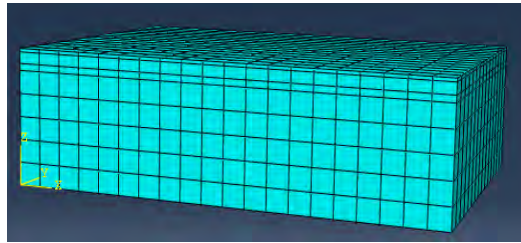


Figure 1: Computing model meshing

CALCULATION RESULTS AND ANALYSIS

When the void ratio of sand cushion is 0.15, 0.25 and 0.35 respectively, the distribution and variation with the time of pore water pressure in cushion have been simulated in the condition of the different void ratio. The calculated results are shown in Figure 2. The variation with the time of pore water pressure in the middle of road and in different time is shown in Figure 3. The calculation results show that:

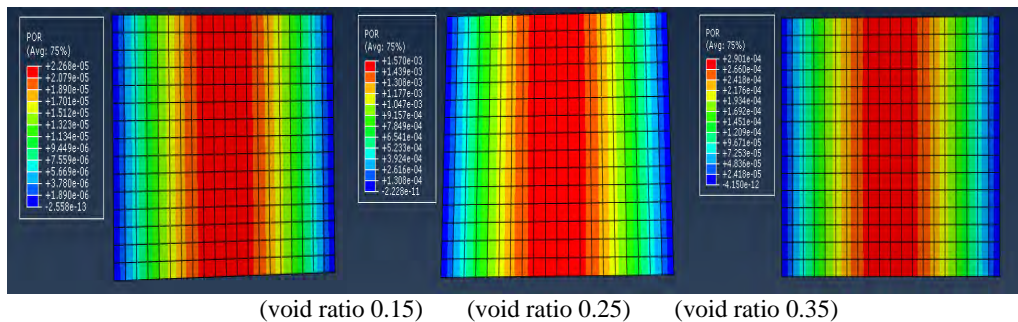


Figure 2: Pore pressure distribution for the void ratio 0.15, 0.25 and 0.35

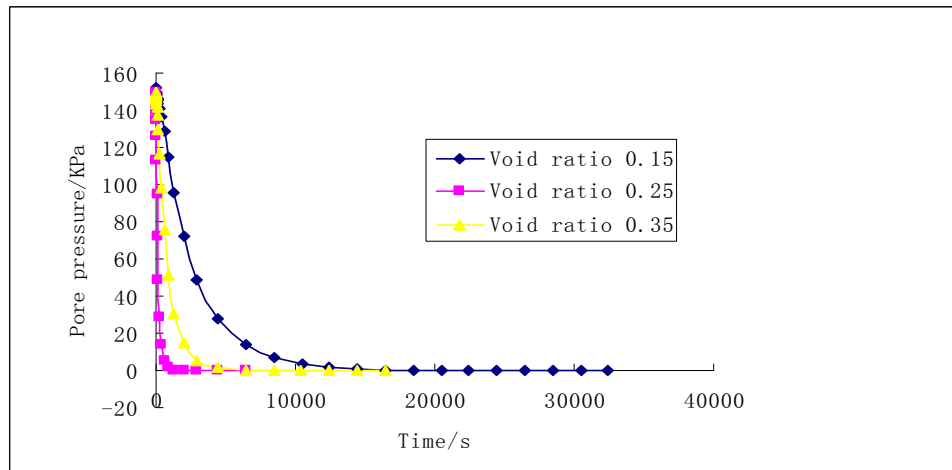


Figure 3: Pore pressure in the road central vs. time for the void ratio 0.15, 0.25 and 0.35

When the void ratio is 0.35, rolling load is 50kPa, 150kPa or 250kPa respectively. The variation of pore water pressure with time has been simulated in different rolling load. The calculation results are shown in Figure 4.

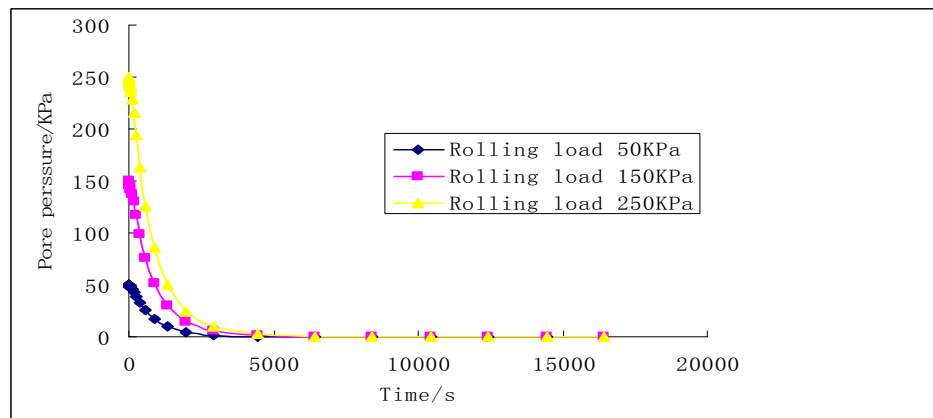


Figure 4: Pore pressure in the road central vs. time for the void ratio 0.35 and rolling load 50kPa, 150kPa or 250kPa

The results show that: When the load is 150kPa and the void ratio is 0.25, the variation of the pore water pressure and pore ratio with time in the middle and the edge of the road are shown in Figure 5 and Figure 6.

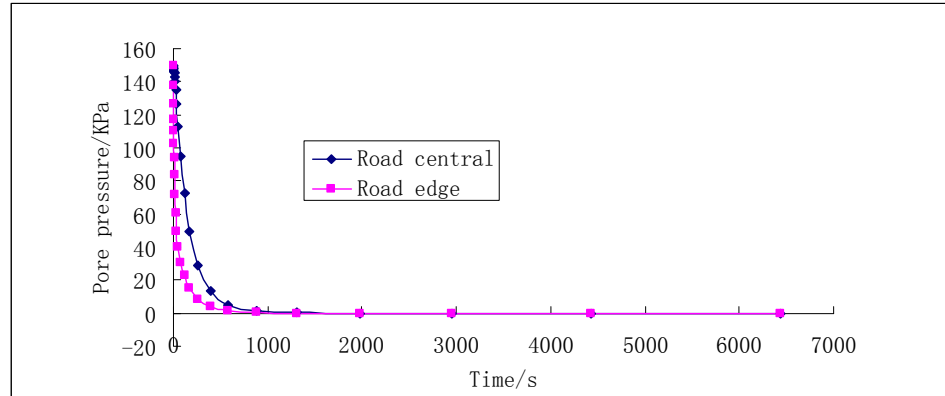


Figure 5: Pore pressure in the road central and edge vs. time for void ratio 0.25 and rolling load 150kPa

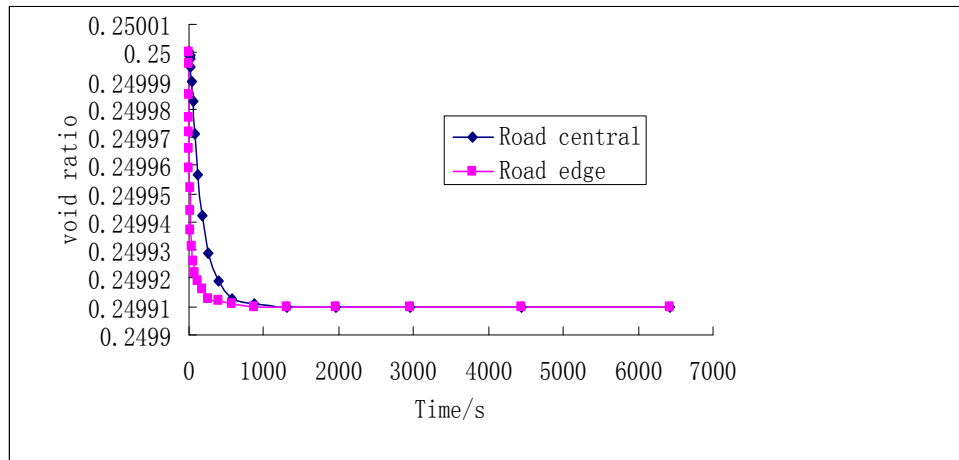


Figure 6: Void ratio in the road central and edge vs. time for void ratio 0.25 and rolling load 150kPa

The results on various working conditions are shown in Table 2 and Table 3 .

Table 2: Drainage process in different pore ratio for rolling load 150kPa

| Void ratio | Permeability m/s | Dewatering time s | Maximum pore pressure kPa | Minimum pore pressure kPa |
|------------|---------------------|----------------------|------------------------------|------------------------------|
| 0.15 | 2E-7 | 3.24E4 | 1.57E-3 | -2.37E-11 |
| 0.25 | 6E-7 | 6435 | 2.27E-5 | -2.56E-12 |
| 0.35 | 1E-6 | 1.64E4 | 2.93E-4 | -4.15E-12 |

Table 3: Drainage process in different rolling load for void ratio 0.35

| Rolling load (kPa) | Dewatering time (s) | Maximum pore pressure (kPa) | Minimum pore pressure kPa |
|-----------------------|------------------------|--------------------------------|------------------------------|
| 50 | 1.64E4 | 4.11E-4 | -5.91E-12 |
| 150 | 1.64E4 | 2.93E-4 | -4.15E-12 |
| 250 | 1.64E4 | 4.79E-4 | -7.28E-12 |

CONCLUSION

In this paper, based on fluid-solid coupling theory, the drainage consolidation process of saturated sand cushion in different void ratio and rolling loads has been simulated using Abaqus finite element software. The results are as follow:

(1) In the rolling load, both maximum pore pressure and maximum void ratio appear in the middle of the road, and they are banded and symmetric by highway profile. In addition, pore pressure and void ratio could reduce gradually from the middle of the road to the edge of the road. The pore pressure and void ratio reduce more slowly in the middle than in the edge.

(2) When the rolling load is 150kPa and void ratio is 0.25, there are most ideal consolidation speed and degree of consolidation. We can draw the conclusion that the drainage effect is most ideal in a best void ratio.

(3) Pore pressure in the early stage reduces very significantly, then stabilized, which shows that most of the free water is discharged and the drainage effect is good in early stage.

(4) When the void ratio is 0.35, there is the same drainage time in different rolling load, which shows that load is no effect on the drainage time with the same porosity. When the load is 150kPa, degree of consolidation is the highest, which illustrates that drainage effect is most ideal at an optimum load.

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