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Structural Response Analysis of Nonlinear Pavement Based on Granular Material

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Abstract. For containing gravel layer structure of flexible asphalt concrete pavement structure, the response laws of gravel pavement structure under elastic and nonlinear were comparatively analyzed through the UMAT subroutine programming and FEM. The results show that when considering the nonlinearity of gravel base, the tensile stress and vertical stress of base layer in pavement structure are quite different from linearity condition. With the increase of the load, the tensile stress of the base layer increases nonlinearly, and is less than that of the elastic gravel material under heavy load. Considering the non-linear condition of gravel, the vertical stress of pavement structure increases and mainly occurs in the gravel base.

1. Introduction

Semi-rigid base asphalt pavement is widely used in China's high grade highway because of its high bearing capacity, strength and performance. However, there are still many shortcomings in this kind of pavement structure, Such as high stiffness lower in permeability and easy to produce reflection cracks, etch [1].This phenomenon has aroused the high attention of road workers, which has gradually broken the single form of semi-rigid basement pavement in China, appearing flexible asphalt pavement that take the grading macadam. Recently, Asphalt gravel, especially graded grading macadam, has been proven to have good performance in stress releasing, drainage and preventing reflective cracks that has been used in high-grade pavement design in some areas. [2] However, grading macadam aggregate have a low modulus and exhibit a large nonlinearity due to the looseness of the aggregate. These two aspects have become the main reasons restricting its application and become the focus of domestic and foreign research [3].

At present, regarding the nonlinear constitutive relationship of the granular base, various models have been proposed at home and abroad, and the regression analysis of the model parameters has been carried out through a large number of indoor triaxial tests. The most important thing of application of granular base is how to apply these results into pavement design. The finite element method has been widely used in pavement structure design. Finite element software, such as ABAQUS, is favored by designers because of its powerful functions. For example, designers can use UMAT subroutine to import nonlinear model of road material into software for analysis. However, the nonlinearity of most material is based on the constitutive relationships of elastoplastic and viscoelastic of materials, The elastic modulus of the granular materials, like gravel, changes with the stress state whose constitutive relation exhibits elastic nonlinearity and that cannot be ignored. This paper is aimed at the nonlinear characteristics of granular materials, Though a summary analysis of its nonlinear constitutive model, we could analysis the change between the linear and nonlinear constitutive structure of granular base structure and the respond of pavement structure, providing a theoretical basis for the design and maintenance of the pavement structure, providing a theoretical basis for the design and maintenance of the pavement structure.

2. Nonlinear Constitutive Model of Granular Base

After the road surface is subjected to long-term load, the permanent deformation of the primary load is very small, so under the repeated action of traffic load, most of the road deformation is considered to be recoverable elastic deformation. But due to the looseness of the aggregate, the elastic modulus will change with the stress [4]. The nonlinear properties of the granule base material have been well known whose research also has gone through a long period of time. Earlier, Lekarp[5] try to set a systematically description to this aspect, pointing out that the stiffness of the base and subbase materials is mainly affected by the water content and the stress state of the material. The most important influence is the equivalent stress, followed by the shear stress in stress. Subsequently, many scholars experimented with the granular base and proposed a series of stress-dependent models characterized by elastic modulus. Such as formula(1)~(7).

$$M_R = k_1 \sigma_3^{k_2} \quad \text{(Seed et al. 1967)} \tag{1}$$

$$M_R = k_1 \theta^{k_2} \quad \text{(Hicks and Monismith 1971)} \tag{2}$$

$$M_R = k_1 \theta^{k_2} \sigma_d^{k_3} \quad \text{(Uzan 1985)} \tag{3}$$

$$M_R = k_1 \theta^{k_2} \tau_{oct}^{k_3} \quad \text{(Witczak and Uzan 1988)} \tag{4}$$

$$M_R = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}\right)^{k_3} \quad \text{(Witczak and Uzan 1988)} \tag{5}$$

$$M_R = k_1 P_a \left(\frac{q - 3k_6}{P_a}\right)^{k_2} \left(\frac{t_{oct}}{P_a} + k_7\right)^{k_3} \quad \text{(NCHRP 2004)} \tag{6}$$

$$M_R = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3} \quad \text{(ARA, Inc. 2004)} \tag{7}$$

Among them

$\theta = \sigma_1 + \sigma_2 + \sigma_3$, First stress invariant;

$\sigma_d = \sigma_1 - \sigma_3$, deviatory stress;

$\tau_{oct} = \dfrac{\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}}{3}$, octahedral shear stress;

P_a——atmospheric pressure, $p_a = 1.03 \times 10^5$;

k_1, k_2, k_3, k_6, k_7—— multiple linear regression parameter;

At present, the ARA model in equation (7) is used extensively in the stress-dependent model of aggregate materials. Dieter [6] repeated experiments on different grades and water content of gravel by indoor dynamic triaxial test. Using this model for regression analysis, the average value of material model parameters was obtained.

$k_1 = 128.5MPa$ (average), $k_2 = 0.520$ (average), $k_3 = -0.1$ (average)

k_2 Mainly represents the sensitivity of aggregate modulus to stress changes. The more sensitive the material, the larger the K; The size of k_3, ranging from -0.4 to 0.6, is mainly affected by water content and k_2.

For the nonlinear model of grain material, domestic scholars Yingjun Mei and Naixing Liang [7] combined with the actual situation, referenced the Wellner model, and introduced the LH nonlinear

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model:

$$E = \left(a + b\sigma_1\right)\sigma_3 + c \tag{8}$$

Tianqing Ling [8] established the regression model relationship between the rebound modulus of the granular base and the thickness of it and the modulus of underlying stratum in 2004:

$$E_2 = \left(ah_2^b\right)E_0 \tag{9}$$

h_2 is structural course thickness of naturally graded aggregate; E_0 is Rebound modulus of the cushion of the corresponding measuring point; a, b are coefficients related to the type of material.

Through regression test and overseas relevant information, we figure out a=0.92 and b=0.40, meanwhile it is found out that the model can be directly used for nonlinear analysis of flexible pavement structures.

3. Nonlinear Algorithm of Finite Element

3.1. Fundamental Principle of nonlinear Algorithm of Finite Element

The finite element analysis firstly discretizes the structure into finite elements, and selects the element as the research object. By introducing the shape function, the relationship between the displacement of the element node and any displacement of point inside the unit is established.

$$\{d\} = [N]\{q\}^e$$

$\{d\}$ is displacement of point inside the unit; $[N]$is shape function of a certain point, which only related to the location of the point; $\{q\}^e$ is shift of element node.

After obtaining the displacement expression of a certain point inside the element, the relationship between the displacement of the element node and strain of any point inside the unit can be established by the geometric equation:

$$\{\xi\} = [L]\{d\} = [L][N]\{q\}^e = [B]\{q\}^e$$

Then, the relationship between the displacement of the element node and the internal stress of the element can be obtained by the physical equation:

$$\{\sigma\} = [D]\{\xi\} = [D][B]\{q\}^e \tag{10}$$

$[B]$ is a constant which is related to the position of the element node; $[D]$Is stiffness matrix.

Using the principle of virtual work, the work done by the node on the virtual displacement is equal to the virtual strain energy of the element, which can be obtained:

$$\delta W = \delta U \Rightarrow \{\delta q\}^{eT}\{F\}^e = \int_V \{\delta\xi\}^T \{\sigma\}\, dV$$

Substituting the formula (2) into the above equation can get to the link between the external force and the displacement of the unit node. the unit characteristic equation is as follows:

$$\{F\}^e = [k]^e\{q\}^e \tag{11}$$

Among them, $[k]^e = [B]^{\mathrm{T}}[D][B]^{\mathrm{T}}$, is element stiffness matrix

However, the unit characteristic equation cannot be used to find the displacement of the element node. It is needed to establish the relationship between the external force of the structure and the displacement of all the element nodes in the structure. It is necessary to add the element characteristic equation to eliminate the influence of the internal force. We apply balance equations to all nodes:

$$\sum_{i=1}^{n}\sum_{e}\sum_{s=i,j...}\left[k_{is}\right]\left\{q_s\right\}^e=\sum_{i=1}^{n}R_i \qquad \text{Or} \qquad \left[K\right]\left\{q\right\}=\left\{R\right\}$$

where n is the number of structural element, s is the number of nodes in a element, $\left[k\right]$ is element stiffness matrix, $\left[K\right]$ is total stiffness matrix.

The essence of finite element calculation is to obtain the total stiffness matrix. The total stiffness matrix can be used to get the displacement of each element node according to the external force, and then the internal displacement, stress and strain of the element are acquired by the shape function, geometric and physical equation. The whole process is shown in Figure 1.

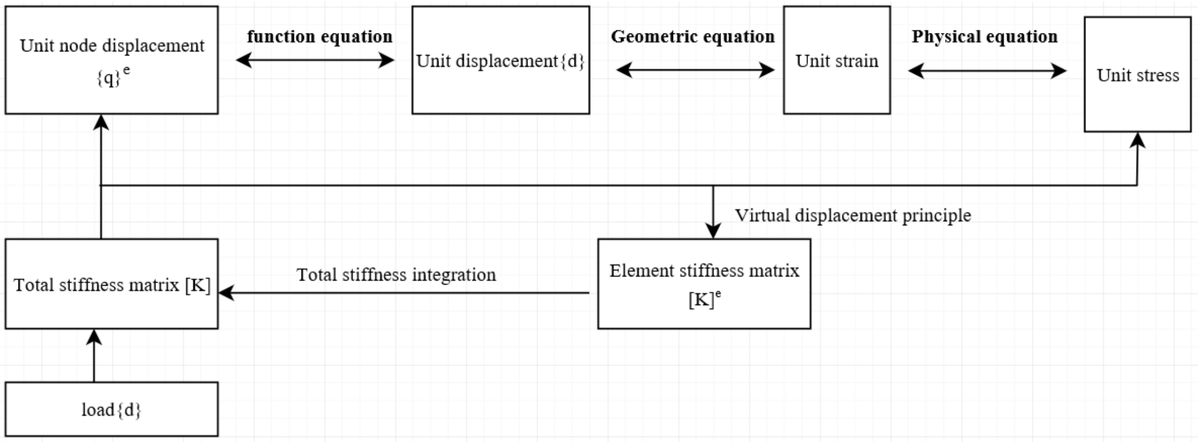


Figure 1. Fundamental principle of finite element solution

It can be seen from the above process that the total stiffness matrix is synthesized by the element stiffness matrix, the element stiffness matrix is related to the stiffness matrixd D, which is composed of the material's elastic modulus E and Poisson's ratio μ.

When the material exhibits nonlinearity and the elastic modulus E changes with the change of stress, the structural load is applied step by step by incremental method and tends to be finalized. In each incremental step we need to solve multiple equations to find the structural balance, and seek an acceptable solution for the incremental step. In each incremental step, the condition of structural balance is that the force generated by the external load on the node is approximately equal to the internal force at the same.

$$\boldsymbol{P} - \boldsymbol{I} = \mathbf{0}$$

In an incremental step, to acquire an approximate solution, there is loop iteration on the above equation. The iteration formula is as follows:

$$\left\{\Delta\delta^e\right\}=\left[{}^tK\right]^{-1}\left\{\Delta F\right\}$$
$$\left\{{}^{t+1}F^e\right\}=\left\{{}^tF^e\right\}+\left[{}^tK^e\right]\left\{\Delta\delta^e\right\}$$

Among them, $\left[{}^tK^e\right]=\int B^{\mathrm{T}}DBdV=\int B^{\mathrm{T}}f\left({}^t\sigma^e,{}^t\xi^e,\Delta\xi^e\right)$, is Element stiffness matrix when the iterating step arrive at t; $\left[{}^tK\right]=\sum\left[{}^tK^e\right]$, total stiffness matrix for the iterating step t.

The calculation process of analysis of nonlinear finite element is shown in Figure 2.

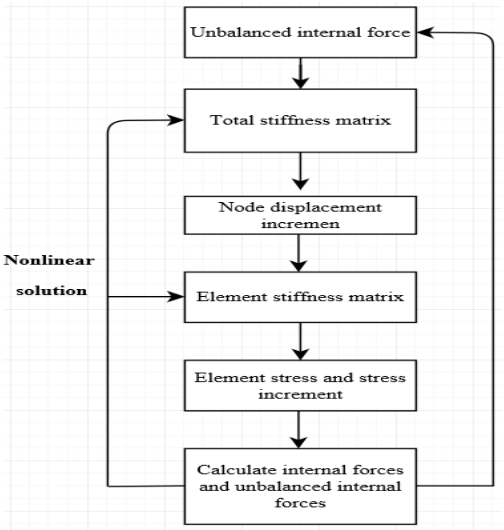


Figure 2. Process of nonlinear solution

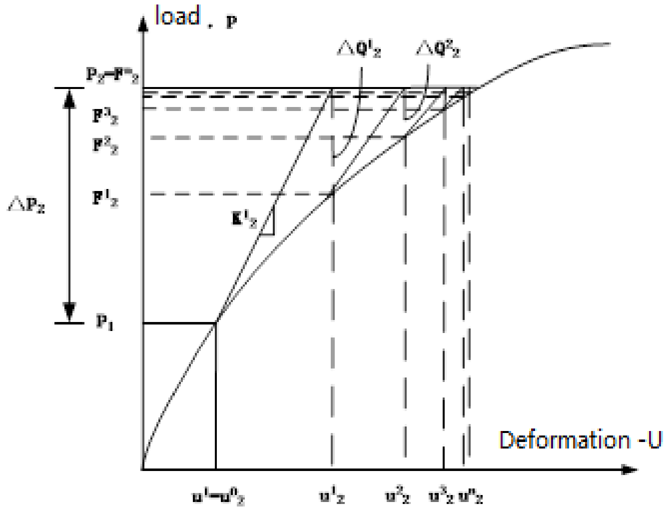


Figure 3. Tangent stiffness algorithm

3.2. Tangent Stiffness Method

The nonlinear finite element mostly uses the incremental iterative method, but in order to ensure the iterative convergence in each incremental step, which need to adopt different algorithms for different constitutive models. The elastic nonlinear model of the gravel subbase and soil foundation is relatively simple. The secant, tangent and constant stiffness method can be used to calculate. Elastic-plastic materials, when their stress can be expressed as a continuous and ductile function of strain, generally adopt the tangent stiffness method, which is also applicable to gravel materials.

A stress softening material refers to a material whose material's elastic modulus has a decreasing tendency as the stress increases, such as some special soil foundation. For this material, in order to ensure iterative convergence, we should take the tangent stiffness method as shown in Figure 3. In the figure,P_1 is the load increment; F^1_2 is the load increment in the 2nd incremental step after the 1st iteration; u^1_2 is the total deformation in the 2nd incremental step after the 1st iteration; K^1_2 is The tangent stiffness at the beginning of the 2nd increment step that corresponds to the overall stiffness matrix of the model; $\Delta Q^1_2 = P_2 - F^1_2$, which is the unbalanced internal force after the first iteration; N is the number of iterations.

Combined with the general process of finite element analysis, the iterative algorithm process of stress softening material in the analysis step is as follows:

Step 1: Calculate the displacement increment of node from the load increment,

$$\Delta u_2^1 = \left[K_2^1 \right]^{-1} \Delta P_2$$

Step 2: Update node displacement and calculate element strain:

$$u_2^1 = u_2^0 + \Delta u_2^1, \varepsilon_2^1 = B u_2^1$$

Step 3: Solving element stress by element strain:

$$\sigma_2^1 = D \varepsilon_2^1$$

In this process, the elastic matrix D is not a constant, but a function of the stress state, which is expressed by the formula $D = f(\sigma)$, and the result of the elastic matrix is approximated in term of the stress state at the beginning of the iterative step.

Step 4: Calculate the elastic matrix of the current material and update the overall stiffness matrix according to the stress magnitude and material of nonlinear model obtained in step 2.

$$D(M_R) = f(\sigma_2^1), S_2^2 = \int_V B^{\mathrm{T}} DBdV$$

Step 5: Calculating internal node stress

$$F_2^1 = \int B^{\mathrm{T}} \sigma_2^1 dV$$

Step 6: Calculate unbalanced internal forces

$$\Delta Q_2^1 = P_2 - F_2^1$$

Return to step 1, we substitute ΔQ_2^1 with ΔP_2 to continue the loop, until Δu_2^n and ΔQ_2^n are less than the allowable value, then enter to the next incremental step.

After each iteration is complete, it needs to be updated stress. For gravel stress hardening materials, the stress update after iteration is shown in Figure 4.

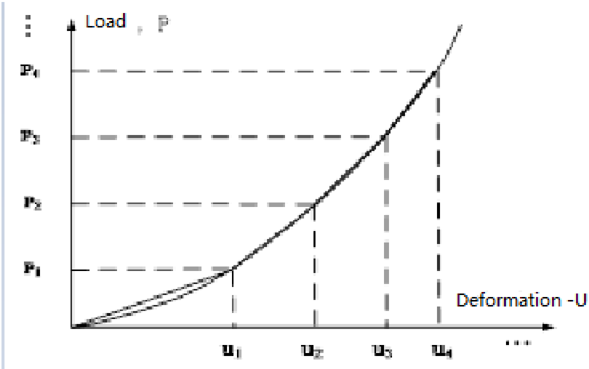


Figure 4. Stress update after iteration

4. Calculation and Analysis of Pavement Structure

4.1. Pavement Analysis Model

The pavement result model usually adopts a half-space infinite extension model. Therefore, to accurately predict the mechanical response of the pavement result, it is necessary to select an appropriate size of the pavement finite element model. Studies have shown that, when the horizontal dimension of the model is 20 times as big as the equivalent circle radius and the vertical dimension is 140 times, the road response of the uniaxial load can be better predicted. Therefore, the selection level of model size: 20R=20*0.213=4.26m; Vertical: 140R: 70*0.213=14.91m.

To ensure that the structure is easy to converge and facilitate meshing, the double rounds uniform load in the specification is converted into the following shape of load distribution. The final model of the pavement structure is shown in Figure 6.

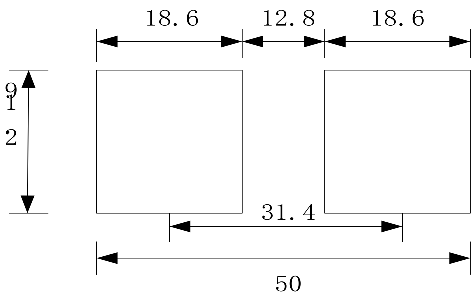


Figure 5. Rectangular load size (unit: cm)

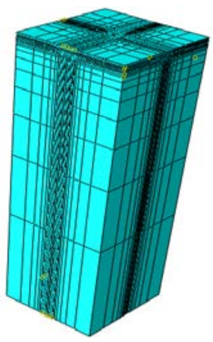


Figure 6. Finite model of pavement structure

4.2. Selection of Pavement Structure Size and Material Parameters
In China, graded gravel is mainly used for the transition layer, base course, and sub base of the road structure [10] .To study the difference of the pavement structure between the linear elastic and nonlinear conditions, the graded gravel is selected as the sub base, As shown in Table 1, the sand cushion in the typical pavement structure was removed for ease of calculation.

Table 1. Asphalt pavement structure of gravel sub base

layer	thickness	modulus	Poisson ratio
Asphalt surface	10	1200	0.3
Asphalt macadam base	10	800	0.35
crushed stone subbase	20	200	0.25
natural gravel cushion	-	-	-
soil	(14.36m)	100	0.3

In this calculation, the structural layers of the pavement are regarded as linear elastic structures except the graded gravel. For the nonlinear structural model of graded gravel, the widely used ARA model is selected for calculation. There are three different crushed stone whose nonlinear model parameters are shown in Table 2 [11].

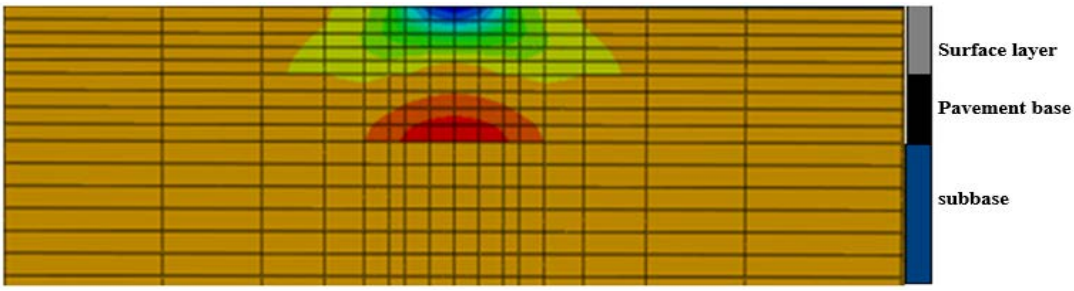
Table 2. Selection of gravel material parameters

Gradation type	model	K_1 (KPa)	K_2	K_3	Initial elastic modulus
Continuous grading(SH1)	ARA	969.32	0.71	-0.04	200MPa
Gab grading(SH2)	ARA	1125.05	0.657	-0.012	200MPa
Design grading(SH3)	ARA	1147.78	0.623	0.073	200KPa

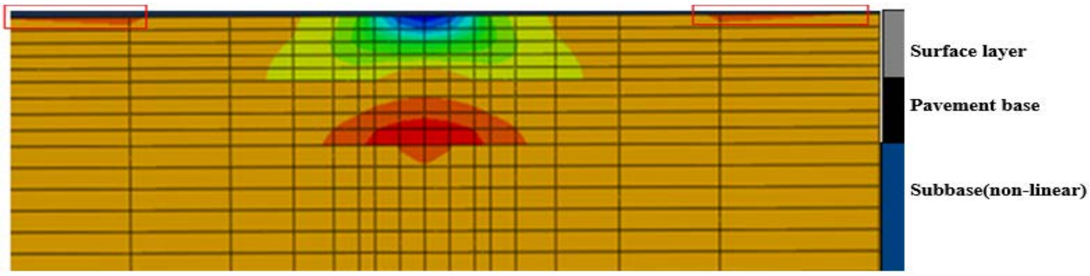
4.3. Calculation Results and Analysis
After finite element calculation, the results show that the nonlinearity of crushed stone sub base material has a significant impact on the tensile stress of the bottom of the base course and the longitudinal stress of the pavement structure.

(1) Influence on the tensile stress of the base course

Figure 7 shows the tensile stress-strain diagram under elastic and nonlinear conditions of the gravel base when the load is 0.7MPa. As can be seen from the chart, when considering the bottom base's nonlinearity, the tensile stress-strain diagram is approximately the same as that under elastic conditions, but under nonlinear terms, the tensile stress has appeared on both sides of the road surface load and the top of the bottom subbase.



(a)Tensile stress-strain diagram under elastic



(b)Tensile stress-strain diagram under nonlinear conditions of the gravel base

Figure 7. Tensile stress-strain diagram under elastic and nonlinear conditions of the gravel base

The maximum tensile stress at the bottom of the base course under elastic and nonlinear conditions varies with the load, as shown in figure 8. It can show from the picture that, as the load increases, the tensile stress at the bottom of the base under elastic conditions increases linearly, while the base course under the nonlinear condition, the growth of the tensile stress of the base appears to be nonlinear. When the base is elastic, its modulus of resilience is 200MPa, but under nonlinear conditions, its variation range is 150MPa~350MPa. In terms of the nonlinear model of macadam, the elastic modulus of materials is proportional to the stress. Therefore, when the road load is small, the elastic modulus and stiffness of the base course are low, which makes the maximum tensile stress of the base under the nonlinear condition larger than that under the elastic condition. However, under the heavy load (such as 1.5MPa), the gravel subbase becomes stiffer due to the increased force. So that the maximum tensile stress at the bottom is less than the elastic condition under nonlinear conditions. It indicates that under heavy load conditions, the nonlinearity of the subbase has a favorable influence on the pressure of base.

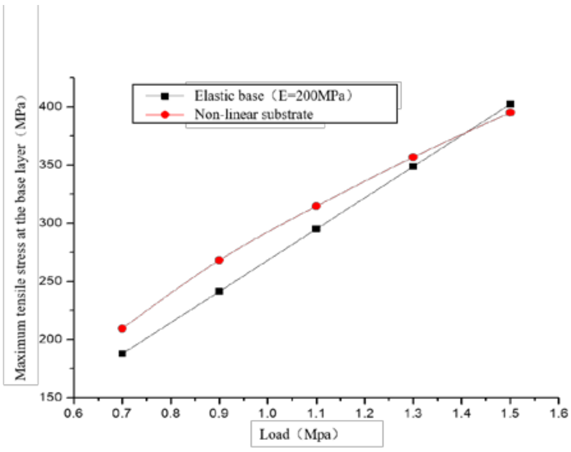


Figure 8. The maximum tensile stress at the bottom of the base course changes with the load

(2) Influence on longitudinal force of pavement structure

Under the conditions of elasticity and nonlinear subbase, the vertical stress diagram of the road structure with a heavy load of 1.5mpa is shown in figure 9. It can be found from the value that the longitudinal stress under the two conditions is different, and the load has an increasing influence on the stress of the base course under the nonlinear terms of the subbase. Figure 10 reflects the variation of vertical pressure along the depth direction under elastic and nonlinear conditions. The red line in the right picture is the selected longitudinal node connection. As shown in the figure, the vertical stress under the nonlinear terms of the subbase is more magnificent than under the elastic condition. Among them, the increase of vertical pressure under the nonlinear condition varies with depth, as shown in Fig. 11. Because the rise of vertical stress mainly occurs on the subbase, it also has a significant influence on the base stress but has a small impact on the soil foundation and surface course.

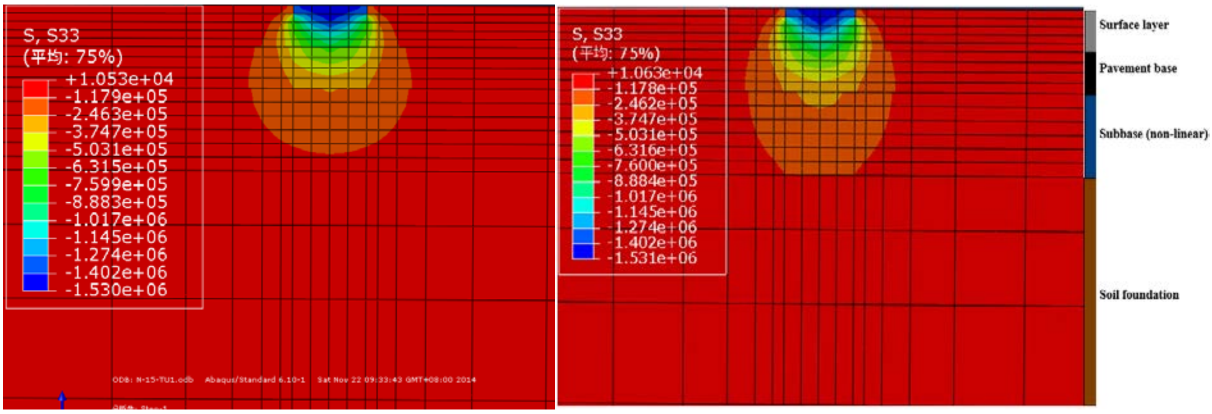


Figure 9. Vertical stress cloud diagram of pavement structure
(elastic on the left and non-linear on the right)

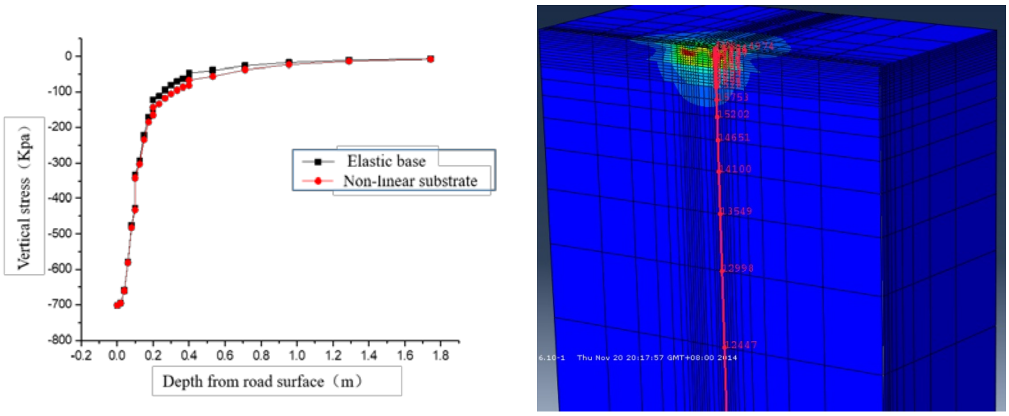


Figure 10. Variation of vertical stress along the depth direction under heavy load (1.5 MPa) elastic and nonlinear conditions

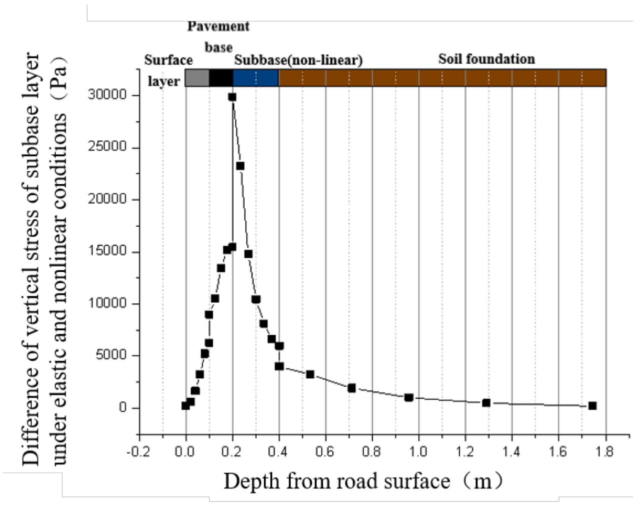


Figure 11. Change of vertical stress between elastic and nonlinear conditions along the depth direction

5. Conclusion

In this paper, the nonlinear finite element analysis of the flexible asphalt pavement structure with gravel structure is carried out by writing the nonlinear constitutive relation subroutine of gravel material. What is important is the difference of pavement structure response under the elastic and

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nonlinear conditions of gravel material. The results show that the longitudinal stress of the pavement is more significant when the nonlinearity of the gravel material is considered. Under the heavy load condition, the base tensile stress under the nonlinearity of the gravel material is smaller than that under the elastic condition. The research results can provide a reference for the design and research of flexible asphalt pavement.

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