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Loading Stress Analysis of Cement Concrete Pavement in Mountainous Areas

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Abstract: The suitable cement concrete pavement for mountainous areas is a form of low-cost cement concrete pavement that uses unconventional graded stones in different proportions in ordinary concrete, allowing the concrete to fully contact the stones and form a stable and well-bonded slab with large particle stones. As large particle stones replace a certain volume of cement concrete, they have good economic performance and are a low-cost form of cement concrete pavement. This study researches the use of ANSYS tools to analyze the influence of geometric dimensions and material properties of rigid pavement structural layers on the mechanical properties of pavement structures.

Keywords: Pavement engineering; Suitable cement concrete pavement for mountainous areas; Finite element analysis; Mechanical property

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1. Preface

In 2003, the Ministry of Transport proposed a strategic plan for the development of county-level and rural roads, proposing to build 100,000 to 200,000 km of township and rural roads annually. The research project "Technology and Process of Suitable Cement Concrete Pavement in Mountainous Areas" focuses on the characteristics of road construction materials and road traffic in mountainous and semi-mountainous areas. By using materials such as excavated stones and river pebbles as additives to cement concrete, the concrete fully contacts with the stones, forming a stable and well-cemented slab. Since large particle stones can replace cement concrete with equal volume while meeting mechanical properties, the economic performance can be greatly improved [1].

2. Calculation model

In the process of calculating the load stress of cement concrete pavement, the assumption of inter-layer sliding is adopted to describe the contact conditions between the slab and the foundation. This assumption is based on the influence of factors such as the type, composition, and usage process of the base material on the inter-layer contact condition. However, in practical situations, the inter-layer contact condition is not completely fixed but shows a changing state between continuous and sliding [2].

This study adopts a model of a finite size four-sided free thick plate on an elastic foundation, and the contact between the plate and the foundation is arbitrary. Moreover, considering practical operability, the focus is on stress calculation and analysis for smooth and continuous extreme conditions [3].

3. Three-dimensional finite element analysis of road load stress

To deeply explore the stress and displacement characteristics of pavement structures under load, this study uses three-dimensional isoparametric elements to discretize and numerically solve concrete slabs. To simulate different bonding situations between layers, this study introduces orthogonal anisotropic contact elements between concrete slabs and foundations [4].

3.1. Basic theory of three dimensional isoparametric element method

The basic formula of the three-dimensional twenty-node isoparametric element method is:

Coordinate transformation formula: $X=\sum_{i=1}^{20} N_i X_i \quad Y=\sum_{i=1}^{20} N_i Y_i \quad Z=\sum_{i=1}^{20} N_i Z_i$

Displacement mode: $u=\sum_{i=1}^{20} N_i u_i \quad v=\sum_{i=1}^{20} N_i v_i \quad w=\sum_{i=1}^{20} N_i w_i$

Strain matrix: $\{\varepsilon\}=[B_i]\{\delta_i\}(i=1,2,\ldots 20)$

Stress matrix: $\{\sigma\}=[D][B]\{\delta\}^e$

Element stiffness matrix: $[K]=\iiint[B]^T[D][B]dxdydz$

Load matrix: $\{R\}=\iiint[N]^T\{q\}ds$

By collecting all the stiffness equations of the elements and establishing the balance of the entire structure, the balance equation of the entire structure is represented by the overall stiffness matrix [K], load matrix {R}, and node displacement matrix [δ]:

$[K]\{\delta\}=\{R\}$

By solving the equilibrium equation, the unknown node displacement can be obtained, and the stress can be calculated accordingly [5].

Experience has shown that using curved edge elements for numerical integration, the stress calculated at the integration point has the best accuracy, while the stress calculated at the node has the worst accuracy. This is because the accuracy of interpolation functions is usually poor near the edge of the interpolation region, so the derivative of the shape function and the accuracy of stress inside the element are better than at the boundary of the element.

3.2. Establishment of inter-layer arbitrary contact model

The contact between the concrete slab and the foundation is neither completely continuous nor smooth but between the two. As theoretical research, it is necessary to find a reasonable inter-layer contact model. Introduce surface units between the surface layer and the base layer to simulate the different inter-layer contact conditions between the surface layer and the base layer.

In elastic theory, the equilibrium equations, geometric equations, and coordination equations of isotropic materials are consistent with those of anisotropic materials, but the difference lies in their stress-strain equations [6].

The structural relationship of anisotropic linear elastic materials satisfies the generalized Hooke's law, i.e:

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_x \\ \gamma_y \\ \gamma_z \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_x \\ \tau_y \\ \tau_z \end{Bmatrix}$$

Abbreviated as:

$$\{\varepsilon_x\} = [S]\{\sigma_x\}$$

In the formula, [S] is called the flexibility matrix and is referred to as the flexibility constant.

It can also be written as:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{zx} \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\ c_{21} & c_{22} & c_{23} & c_{24} & c_{25} & c_{26} \\ c_{31} & c_{32} & c_{33} & c_{34} & c_{35} & c_{36} \\ c_{41} & c_{42} & c_{43} & c_{44} & c_{45} & c_{46} \\ c_{51} & c_{52} & c_{53} & c_{54} & c_{55} & c_{56} \\ c_{61} & c_{62} & c_{63} & c_{64} & c_{65} & c_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{zx} \\ \gamma_{xy} \end{Bmatrix}$$

Abbreviated as:

$$\{\sigma_x\} = [C]\{\varepsilon_x\}$$

In the formula, [C] is called the stiffness matrix or modulus matrix, and is called the elastic constant. The flexibility matrix and modulus matrix are mutually inverse, i.e:

$$[C] = [S]^{-1}, [S] = [C]^{-1}$$

In general, each strain component in an anisotropic body is a linear function of all stress components. Represented in tensor form as:

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$$

This is the generalized Hooke’s law, also known as the constitutive relationship equation. Since stress and strain are both second-order tensors, in three-dimensional space, the stiffness matrix is a fourth-order tensor containing elements that represent a corresponding elastic constant.

In this way, the contact layer becomes a part of the foundation, and the entire structure becomes an isotropic linear elastic body that is completely continuous between layers. The load stress analysis of the structure is completely equivalent to the theory and method used by isotropic three-dimensional isoparametric elements.

3.3. Completely continuous stress analysis of plate and foundation

The basic calculation model is a finite size four-sided free plate on an elastic foundation, and the plate is in continuous contact with the base layer. The basic load is taken as the single rear axle double wheel group wheel load, with an axle load of 100 kN and a pressure of 0.7 MPa. For the convenience of finite element analysis and calculation, the load application surface is taken as a square with a side length of 18.9 cm.

3.3.1. Analysis of stress at the bottom of concrete slabs based on the geometric dimensions of the foundation

When using spatial isoparametric elements to calculate elastic layered structures, its convergence is influenced by the rationality of element partitioning and the choice of calculation area size. Under the condition of ensuring that the calculation range is sufficiently broad and the density of units is coordinated with the field gradient, the calculation results will approach an accurate solution [6].

The parameters used for calculation are: the plane size of the board is 5 × 6 m^2, and the board thickness is 25 cm; The base layer (Lime-fly Ash Macadam) is 6 m wide, equal in length to the foundation, with a thickness of 2 × 16 cm; The plane dimension of the elastic foundation is, with a depth of z (m). The material parameters are shown in **Table 1**.

The model established using ANSYS 10.0 finite element program is shown in **Figure 1** and **Figure 2**.

The maximum stress calculation results at the bottom of the plate under standard load are shown in **Table 2**.

Table 1. Physical parameters of materials

Project	Resilience Modulus, E (MPa)	Poisson's Ratio, μ	Thickness, h (m)	Density, ρ (kg/m³)
Road surface layer	33000	0.15	0.25	2700
Lime-fly Ash Macadam	1500	0.2	0.32	2500
Soil base layer	50	0.35		1800

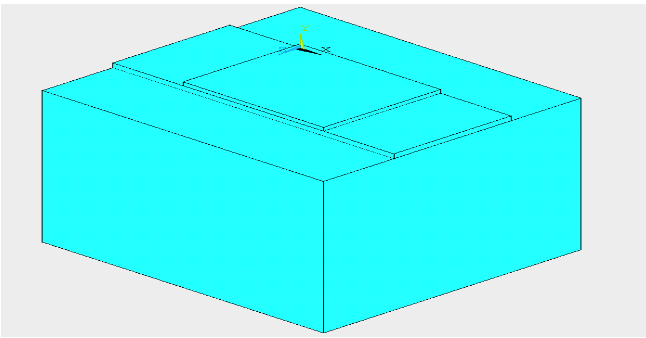

Figure 1. ANSYS finite element calculation model

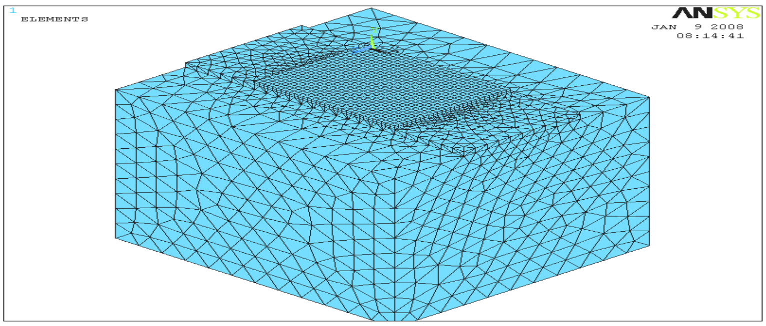

Figure 2. Grid partitioning model

Table 2. Comparison of the plane dimensions of the foundation with the stress of the plate

Identifier	(1)	(2)	(3)	(4)
Foundation size (x,y,z) (m)	7,6,4.5	9,8,4.5	10,9,4.5	11,10,4.5
Calculate point stress value (MPa)	1.2207	1.2855	1.2937	1.3060
Identifier	**(5)**	**(6)**	**(7)**	**(8)**
Foundation size (x,y,z) (m)	12,11,4.5	13,12,4.5	14,13,4.5	20,15,4.5
Calculate point stress value (MPa)	1.3057	1.3038	1.3175	1.3100

From the calculation results in **Table 2**, it is found that when the depth of the foundation is constant, the stress at the bottom of the slab gradually increases with the increase of the geometric size of the foundation plane. When the geometric size of the foundation plane reaches a certain degree, the stress at the bottom of the slab reaches its limit, and the stress at the bottom of the slab gradually increases and converges with the increase of the geometric size of the foundation plane. The impact range of the load on the foundation is a limited area, approximately 12×11 m^2.

The influence of foundation depth on the stress of the slab is calculated in **Table 3**.

Table 3. Foundation depth and bottom stress table

Identifier	(1)	(2)	(3)	(4)
Foundation size (x,y,z) (m)	12,11,4.5	12,11,6	12,11,10	12,11,12.5
Calculate point stress value (MPa)	1.2207	1.3101	1.3252	1.3452
Identifier	**(5)**	**(6)**	**(7)**	**(8)**
Foundation size (x,y,z) (m)	12,11,15	12,11,17.5	12,11,20	12,11,25
Calculate point stress value (MPa)	1.3635	1.3225	1.3223	1.3215

From **Table 3**, it is found that when the geometric plane size of the plate surface is constant, the stress at the bottom of the plate gradually increases with the increase of the foundation depth. When the foundation depth reaches a certain level, the stress at the bottom of the plate reaches its limit. As the foundation continues to deepen, the stress at the bottom of the plate gradually decreases and converges; The influence range of the load on the depth of the foundation is a limited area, approximately 17.5 m. The maximum tensile stress at the bottom of the plate calculated by ANSYS finite element method converges to 1.32 MPa.

3.3.2. Analysis of the effect of geometric dimensions of concrete panels on the load stress at the bottom of the panels

According to the mechanical model of concrete pavement, the influence of base layer on the load stress at the bottom of the slab under the same pavement structure conditions is calculated, and the parameters of the plane size of the concrete slab are 5×6 m^2 and the slab thickness is 25 cm; The base layer (Lime-fly Ash Macadam) is 5 m wide, equal in length to the foundation, with a thickness of 2×16 cm; The geometric dimensions of the elastic foundation are $12 \times 11 \times 17.5$ m^3. The calculation results are shown in **Table 4**.

Table 4. Comparison table of load stress of concrete panel

Size of cement concrete slab (m)	6×5×0.25	6×5×0.25	6×5×0.25	6×5×0.25	6×5×0.25	6×5×0.25	6×5×0.25
Rebound modulus of soil foundation (MPa)	50	50	50	50	50	50	50
Base rebound modulus (MPa)	250	500	750	1000	1300	1500	1700
Loading stress calculation results (MPa)	1.8165	1.6803	1.5700	1.4787	1.3805	1.3217	1.2674

According to the parameters and results calculated in **Table 4**, the tensile stress at the bottom layer of the concrete slab under load gradually decreases with the increase of the elastic modulus of the base layer.

The influence of concrete slab size on the stress at the bottom of the slab, calculation parameters, and results are shown in **Table 5**.

Table 5. Comparison table of concrete panel load stress and plate thickness

Size of cement concrete slab (m)	6×5×0.18	6×5×0.2	6×5×0.22	6×5×0.24	6×5×0.25	6×5×0.26	6×5×0.30
Rebound modulus of soil foundation (MPa)	50	50	50	50	50	50	50
Base rebound modulus (MPa)	1500	1500	1500	1500	1500	1500	1500
Loading stress calculation results (MPa)	2.0731	1.6558	1.5056	1.3777	1.3805	1.2740	1.1009

From the analysis in **Table 5**, it can be concluded that under the same pavement structure and load, as the thickness of the cement concrete slab gradually increases, the maximum tensile stress at the bottom of the BSSC board shows a gradually decreasing trend. Especially when the thickness of the cement concrete slab does not reach 25 cm, the effect of reducing the tensile stress at the bottom of the slab becomes more prominent with the increase of slab thickness. When the cement concrete slab is larger than 25 cm, the tensile stress at the bottom of the slab decreases slowly with the increase of slab thickness. Therefore, the cement concrete pavement is optimal for heavy-duty traffic with a pavement thickness of 25 cm.

3.4. Stress analysis of absolute smooth contact between board and base

Introducing an orthogonal anisotropic contact model to achieve smooth contact between plates and foundations. Since the computational structure is divided into two types of elements, namely ordinary elements and contact elements, they exhibit isotropic linear elasticity and anisotropic linear elasticity in material properties.

Calculations using three-dimensional finite element and plate element under identical conditions were used to compare both methods. The plane calculation size of the cement concrete slab is 480 cm × 360 cm, and the load position is the lateral movement of the axial load in the middle of the slab length. During the trial calculation, the foundation size is taken as small z = 12 × 11 × 17.5 m^3. Parameters of cement concrete slab and base: E_S = 50 MPa, E_c = 33,000 MPa,μ_c = 0.15, μ_s = 0.2, h_c = 25 cm, E_1 = 0.005 MPa, μ_{12} = 0.01, μ_{13} = 0, G_{13} = 0.03 MPa, h_0 = 0.1cm. The calculation results are summarized in **Table 1** to **Table 8**. From the tables, it can be seen that the calculation results using three-dimensional isoparametric elements after introducing orthogonal anisotropic contact elements are consistent with those using plate elements. The maximum error is 1.93%, and the error at the critical load level is only -0.1%, indicating that this article meets the theoretical requirements in terms of computational accuracy when used to simulate absolute smooth contact between layers.

Table 6. Comparison table for calculating the maximum bending tensile stress at the bottom of the plate

Calculate the distance between the point and the center of the board (cm)	Calculation Methods		
	Plate	Absolute smoothness	Completely continuous
2	1.3629	1.3365	1.2848
32	1.5059	1.4795	1.3992
150	1.5939	1.6082	1.5125
180	2.1758	2.1736	2.0713

By calculating and examining the changes in the thickness and modulus ratio of cement concrete slabs h_c, when the modulus ratio E_c / E_S changes, the change in the maximum bending tensile stress at the bottom of the plate is compared with the calculation results of the complete inter-layer continuity. The comparative calculation results are listed in **Table 7** and **Table 8**.

Table 7. Comparison table of normal stress σ for different plate thicknesses

Plate Thickness, h_c (cm)	18	20	22	24	26	28	30
Absolute smoothness	2.073	1.656	1.506	1.378	1.274	1.147	1.101
Completely continuous	2.474	1.968	1.783	1.625	1.488	1.339	1.246
Difference rate (%)	16.2	15.9	15.5	15.2	14.4	14.4	11.6

Table 8. Comparison table of normal stress σ at different modulus ratios

Modulus Ratio, E_c / E_S	33000/ 250	33000/ 500	33000/ 750	33000/ 1000	33000/ 1300	33000/ 1500	33000/ 1700
Absolute smoothness	1.817	1.680	1.570	1.479	1.381	1.322	1.267
Completely continuous	2.285	2.074	1.878	1.750	1.589	1.490	1.413
Difference rate (%)	20.5	19	16.4	15.5	13.1	11.3	10.3

Note: The values in the table are calculated based on h_c = 25 cm

From **Table 7** and **Table 8**, it can be seen that the tensile stress σ at the bottom of the cement concrete slab decreases with h_c increasing, and increases with E_c / E_S increasing. As the thickness and modulus of the plate increase, the influence of inter-layer contact conditions (absolutely smooth or completely continuous) on σ decreases. The influence of boundary conditions on pavement stress-strain is not constant. As the structural and mechanical parameters related to inter-layer contact conditions change (the thickness of the plate increases and the relative stiffness of the plate increases), the degree of influence of inter-layer contact conditions on the maximum bending tensile stress at the bottom of the plate gradually weakens.

4. Conclusion

Based on the theory of anisotropic linear elasticity, this paper successfully constructed an "orthogonal anisotropic contact model". Using this model, combined with the spatial finite element method, the load stress of the elastic foundation slab and the cement concrete pavement structure under any contact conditions can be analyzed in depth to ensure that the analysis accuracy meets the theoretical requirements.

Based on ANSYS finite element theory calculation and analysis, it is recommended that the appropriate thickness of the slab pavement be 25 cm for the actual needs under heavy traffic conditions. At the same time, a large amount of calculation and analysis were conducted on the two extreme cases of smooth contact and continuous contact between the slab pavement and the foundation, to provide reliable reference data for the engineering design department.

Disclosure statement

The authors declare no conflict of interest.

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