Inversion Study on Dynamic Parameters of Moderately Weathered Dolomite

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Abstract: This paper conducts an inversion study on the dynamic elastic modulus and dynamic Poisson's ratio of moderately weathered dolomite using MIDAS/GTS-NX finite element software, with a real estate project in Kunming as the engineering background. Taking the maximum and minimum principal stresses at observation points of tunnel lining as evaluation indicators, the rationality of simplifying the rock's constitutive relation to an elastic one is verified first. The results show that the average relative errors of the maximum and minimum principal stresses under the elastic constitutive relation are 2.9% and 3.0% respectively compared with the Mohr-Coulomb model, indicating good reliability. Through time-history analysis and parameter adjustment, it is concluded that when the dynamic elastic modulus of moderately weathered dolomite is 1-1.15 times the static elastic modulus (19000 MPa) and the dynamic Poisson's ratio is 1-1.24 times the static Poisson's ratio (0.28), the dynamic calculation results are consistent with the actual stress characteristics of the tunnel lining. This study provides a scientific reference for the selection of dynamic parameters of moderately weathered dolomite in seismic design and numerical simulation of underground structures.

Keywords: Dolomite; Dynamic Elastic Modulus; Dynamic Poisson's Ratio; Seismic Design; Time History Analysis

1. Introduction

Fissures are ubiquitous in various types of rocks, primarily caused by two factors: the evolution of natural rock stratification over long periods [1] and fractures generated by external forces. These fissures are one of the main factors affecting the static and dynamic elastic properties of rocks. The closure of fissures increases axial strain and the velocities of P-waves and S-waves [2], while the aperture of axial fissures significantly influences the rock's Poisson's ratio [3]. Consequently, it is often difficult to obtain precise values for elastic modulus and Poisson's ratio during geological surveys. In seismic design, the selection of rock elastic modulus plays a pivotal role in numerical analysis.

Common calculation methods for underground structure seismic design include the static method, pseudo-static method, and dynamic time-history analysis. The static method yields overly crude results and is largely obsolete. The pseudo-static method typically employs the response displacement method and the response acceleration method [4]. Liu et al. verified the practicality of the response displacement method in the transverse seismic analysis of underground structures by studying different displacement methods and soil-structure dynamic interaction [5]. Wang et al. [6] compared the response displacement method with time-history analysis, analyzing changes in tunnel internal forces and horizontal displacements of key nodes under seismic action, proving the applicability of time-history analysis in seismic design. The response displacement method uses a spring structure model; however, the selection of spring stiffness and the inability of the spring system to reflect its own interaction during soil deformation lead to calculation deviations. The response acceleration method ignores damping effects [7]. In complex soil layers, the damping effect on energy dissipation of seismic waves is significant, resulting in obvious calculation errors [8].

Liu et al. [9] conducted research on tunnel seismic response through theoretical calculations and numerical simulations. The results showed that when simulating tunnel seismic response with MIDAS/GTS-NX, the maximum bending moment and shear force of the lining were consistent with values estimated by the loosening circle reduction coefficient method, confirming the feasibility of simulating the instantaneous dynamic response of underground structures under seismic action. Based on a real estate project in Kunming and using MIDAS/GTS-NX software for time-history analysis, this paper takes the maximum and minimum principal stresses at various observation points of the tunnel lining as evaluation indicators. By referencing the stress state of the tunnel lining at various observation points under static conditions, it inversely calculates reasonable stratum dynamic parameters, providing a reference for the selection of dynamic parameter values for moderately weathered dolomite in numerical simulations.

2. Algorithm Principle

The time-history analysis method is a dynamic analysis method that directly solves the motion differential equation of structures through step-by-step integration [10]. In MIDAS/GTS-NX, the HHT-α method is used to implement implicit direct integration. This method is a modified Newmark method that can reduce high-frequency noise and has a time step of second-order accuracy like the Newmark method. The dynamic equilibrium equation of HHT-α is as follows:

$$Ma^{n+1}+\left(1+a_n\right)\left[Cv^{n+1}f^{\text{int},n+1}-f^{ext,n+1}\right]-a_H\left[Cv^n+f^{\text{int},n}+f^{ext,n}\right] \quad (1)$$

Where α_{n+1} and v_{n+1} represent the acceleration and velocity at the (n+1)th time step, respectively, and α_H ∈ [0, 1/3] is the coefficient determining the numerical damping effect. When considering the effect of non-mechanical strain, the internal force of linear analysis can be expressed by Equation (2). Non-mechanical strain refers to strain caused by thermal expansion, initial stratum stress, pore pressure, etc.

$$f^{\text{int},n+1}=Ku^{n+1}-f^{nonmench,n+1}+f^{\text{int},0} \quad (2)$$

According to the time-step equations of the Newmark method, the expressions of velocity, displacement, and acceleration at the nth and (n+1)th time steps are as follows:

$$v_{n+1}=v^n+\Delta t\left[\gamma a^{n+1}+\left(1-\gamma\right)a^n\right] \quad (3)$$

$$u^{n+1}=u^n+\Delta tv^n+{}^1\!/_2\,\Delta t^2\left[2\beta a^{n+1}+\left(1-2\beta\right)a^n\right] \quad (4)$$

Combining Equations (1), (2), (3), and (4), the simultaneous equations at the (n+1)th time step are as follows:

$$K^{eff}u_{n+1}=f^{eff} \quad (5)$$

$$K^{eff}=M\big/\left(\beta\Delta t^2\right)+\left(1+a_H\right)\gamma C/\beta\Delta t+\left(1+a_H\right)K \quad (6)$$

$$\begin{aligned}f^{eff}=&-f^{\text{int},0}+\left(1+a_H\right)\left[f^{ext,n+1}+f^{nonmech,n+1}\right]+\\&M\left[\frac{u^n}{\beta\Delta t^2}+\frac{v^n}{\beta\Delta t^2}+\frac{\left(2\beta-1\right)a^n}{2\beta}\right]+\\&C\left[\frac{\left(1+a_H\right)\gamma u^n}{\beta\Delta t}+\frac{v^n\left\{\left(1+a_H\right)\gamma-\beta\right\}}{\beta}+\frac{a^n\Delta t\left(1+a_H\right)\left(\gamma-2\beta\right)}{2\beta}\right]\end{aligned} \quad (7)$$

Is jointly determined by the displacement, velocity, acceleration, and internal force calculated at the nth time step. The displacement u_{n+1} can be solved by simultaneous equations, and the velocity and acceleration are obtained by substituting into Equation (4). The transient response of the structure can be obtained through iterative calculation.

3. Finite Element Simulation

3.1 Project Background

The net land area of the proposed project is 99,877.28 square meters, and the total construction area is 252,968.28 square meters. The site is located in the section of the 9th marking line of the water conveyance line construction of the Niulan River-Dianchi Lake Water Supplement Project, with mileage 86+857.1~87+217.6 (corresponding to the mileage pile number K8+252.6~K8+613.2 of the Dawu Mountain Tunnel). The Dawu Mountain Tunnel is located below Plot 1 (the proposed site), and the length of the crossing section within the land use red line is 360.2m. The tunnel obliquely passes through the entire site from northeast to southwest (24° north of east), as shown in Figure 1. As a key project among the six major engineering measures for water environment comprehensive management in the Dianchi Lake Basin, the Niulan River-Dianchi Lake Water Supplement Project's 9th marking line Dawu Mountain Tunnel is an important part of the project. The surrounding rock types of this section of the tunnel are mainly Class V~IV surrounding rocks, and individual sections are Class III surrounding rocks, corresponding to the excavation and support types of modified Type V, modified Type IV, and Type III. The tunnel height is 5200mm, and the tunnel lining thickness is 700mm (600mm in individual sections). The schematic diagram of the tunnel is shown in Figure 2. The vertical positional relationship between the tunnel and the surface buildings is shown in Figure 3 below. Meanwhile, the tunnel is located between two regional fault zones: the Pudu River Fault Zone to the west of the site and the Xiaojiang Fault Zone to the east. To protect the normal operation of the Niulan River-Dianchi Lake Water Supplement Project, the impacts of upper buildings and seismic action on the tunnel lining are studied separately.

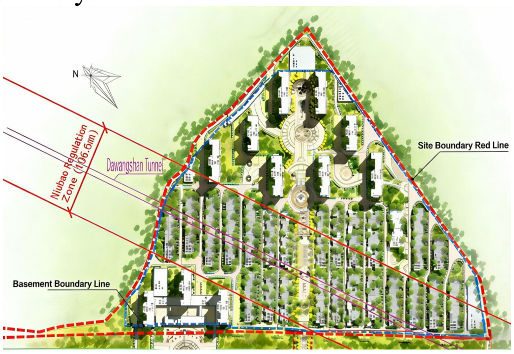

Figure 1. Planar Schematic Diagram of the Relative Position between Plot 1 and the Water Conveyance Line Tunnel

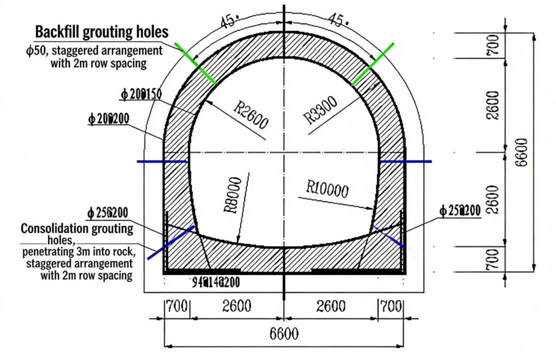

Figure 2. Lining Cross-Section Diagram

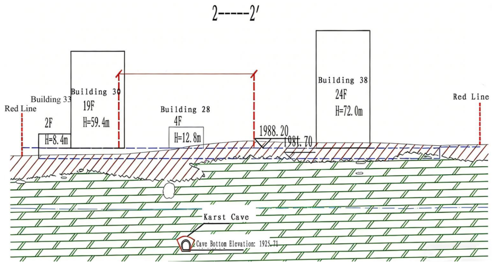

Figure 3. Diagram of the Relationship between the Tunnel and Upper Buildings (Cross-Section Perpendicular to the Tunnel)

3.2 Calculation Model and Parameter Selection

Considering the surface topography, engineering geological conditions, and tunnel burial depth, this paper selects a typical cross-section (taking cross-section 2-2 as an example) and establishes a two-dimensional finite element model using MIDAS/GTS-NX. The model has a length of 382 meters in the horizontal direction (X-direction) and a height of 152 meters in the vertical direction (Y-direction), as shown in Figure 4. The bulk density of C25 concrete is 23.5kN/m³, the elastic modulus is 28GPa, and the Poisson's ratio is 0.2. The main physical parameters of other rock and soil are shown in Table 1.

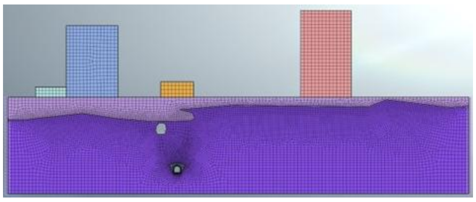

Figure 4. Model of Cross-Section 2-2

Table 1. Rock Mass Parameters

Soil Layer Name	Natural Density (kN/m³)	Cohesion (kPa)	Friction Angle (°)	Static Elastic Modulus (MPa)	Static Poisson's Ratio	Dynamic Elastic Modulus (MPa)	Dynamic Poisson's Ratio
Soft Plastic Red Clay	17	25	5	10	0.4	15	0.45
Moderately Weathered Dolomite	27	300	30	19000	0.28	40000	0.33
Loose Zone	24.5	80	26	8000	0.32	16000	0.36

Considering that the proposed site is located in the Xiaojiang Fault Zone, a Tonghai seismic wave is applied in the vertical direction of the model, and the ground acceleration is scaled by 0.3g. The scaled ground acceleration is shown in Figure 5. The damping used in the seismic analysis is Rayleigh damping. The damping ratio corresponding to the first and second vibration modes is 0.05, and the damping ratios of other vibration modes are calculated according to the Rayleigh damping based on the vibration mode frequency. Meanwhile, observation points are arranged on the tunnel lining, as shown in Figure 6. Dynamic time-history analysis is performed on the section of the 9th marking line of the water conveyance line construction of the Niulan River-Dianchi Lake Water Supplement Project, with mileage 86+857.1~87+217.6 (corresponding to the mileage pile number K8+252.6~K8+613.2 of the Dawu Mountain Tunnel).

To inversely calculate the dynamic elastic modulus and dynamic Poisson's ratio of moderately weathered dolomite, the reasonable constitutive relation of the rock stratum should first be determined. Wang Yuan [11-12] et al. compared four constitutive relations of rocks when studying the brittle failure of hard rocks under high ground stress and found that the maximum principal stress distribution diagram of surrounding rocks calculated using the Mohr-Coulomb model is basically consistent with the calculation results of the elastic model. Therefore, this paper first analyzes the elastic constitutive relation of moderately weathered dolomite, and verifies the rationality of using the elastic model for numerical analysis of moderately weathered dolomite by comparing the stress changes at the observation points of the tunnel lining under static conditions. Then, according to the empirical formula (8) for Poisson's ratio and deformation modulus in rocks proposed by Tang Daming [13] et al.:

$$\mu = 0.4 + 0.05\lg\left(E_0/2\right) \quad (8)$$

Where μ is Poisson's ratio and E_0 is the deformation modulus. When the material is linearly elastic, E_0=E. Therefore, this paper reduces the dynamic elastic modulus of moderately weathered dolomite measured by geological survey and converts the corresponding Poisson's ratio according to the above relationship. By comparing the stress conditions at each observation point under dynamic and static conditions, the reasonable dynamic elastic modulus and dynamic Poisson's ratio of moderately weathered dolomite are finally inversely obtained. The adjusted dynamic elastic modulus and dynamic Poisson's ratio are shown in Table 2.

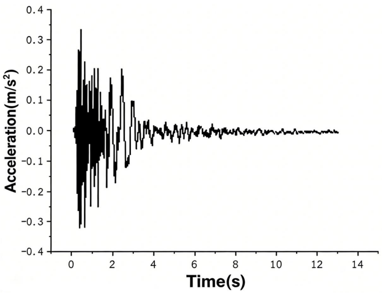

Figure 5. Input Seismic Wave-Tonghai Wave

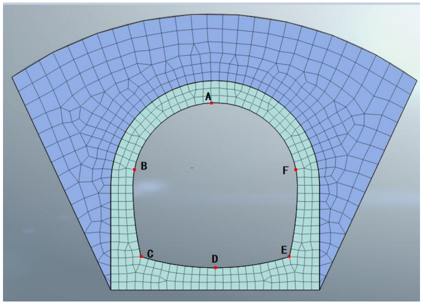

Figure 6. Arrangement of Observation Points on the Tunnel Lining

Table 2. Adjusted Dynamic Parameters of Moderately Weathered Dolomite

Adjustment Coefficient	Dynamic Elastic Modulus (GPa)	Dynamic Poisson's Ratio
1	40	0.33
0.95	38	0.336
0.90	36	0.337
0.85	34	0.338
0.80	32	0.340
0.75	30	0.341
0.70	28	0.343
0.65	26	0.344
0.6	24	0.346
0.55	22	0.347

4. Results Analysis

4.1 Discussion on the Applicability of the Elastic Model

To verify the elastic constitutive relation of moderately weathered dolomite under static conditions. Through the analysis of the maximum principal stress and minimum principal stress at the six observation points in Table 3, it can be concluded that compared with the Mohr-Coulomb constitutive relation, when the elastic constitutive relation is adopted, the average relative error of the maximum principal stress is 2.9%, and the average relative error of the minimum principal stress is 3.0%. This fully indicates that it is reasonable to simplify the constitutive relation of moderately weathered dolomite to an elastic constitutive relation for inverting its dynamic elastic modulus and dynamic Poisson's ratio.

Table 3. Mechanical Parameters at Observation Points

Observation Point	Maximum Principal Stress (kPa)		Average Relative Error (%)	Minimum Principal Stress (kPa)		Average Relative Error (%)
	Mohr-Coulomb	Elastic		Mohr-Coulomb	Elastic	
A	-54.3	-57.2	2.9	-1118.8	-1200.5	3.0
B	-184.1	-180.9		-4345.1	-4327.3	
C	-1423.2	-1425.3		-4918.4	-4912.7	

D	226.4	221.5		-7.2	-7.1	
E	-1455.6	-1385.9		-5057.1	-4828.4	
F	-180.4	-179.8		-4358.1	-4874.9	

4.2 Inversion Analysis of Dynamic Elastic Modulus and Dynamic Poisson's Ratio

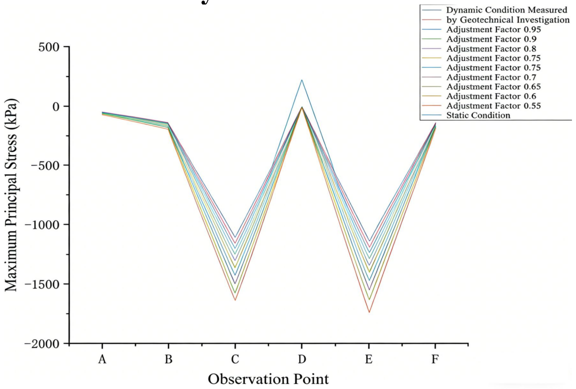

Figure 7. Relationship between Dynamic Elastic Modulus, Dynamic Poisson's Ratio and Maximum Principal Stress at Observation Points

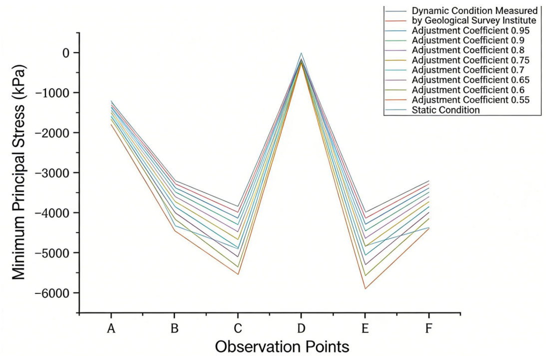

Figure 8. Relationship between Dynamic Elastic Modulus, Dynamic Poisson's Ratio and Minimum Principal Stress at Observation Points

Taking the stress conditions of each measuring point of the tunnel lining under static action as a reference, through the analysis of the maximum principal stress and minimum principal stress at each observation point under dynamic action, as shown in Figures 7 and 8, when the dynamic elastic modulus and dynamic Poisson's ratio of moderately weathered dolomite measured by geological survey are adopted, although the maximum principal stress and minimum principal stress at each observation point meet the "Code for Design of Concrete Structures" and the lining will not be damaged, their values are smaller than those under static action, which is obviously unreasonable. Therefore, the dynamic elastic modulus and dynamic Poisson's ratio are adjusted. Through the above time-history analysis, when the dynamic elastic modulus is 22GPa and the dynamic Poisson's ratio is 0.347, the maximum principal stress and minimum principal stress at each observation point are greater than those under static conditions. In other words, when the dynamic elastic modulus of moderately weathered dolomite is 1-1.15 times the static elastic modulus and the dynamic Poisson's ratio is 1-1.24 times the static Poisson's ratio, the results obtained from dynamic calculations using MIDAS/GTS-NX are relatively reasonable.

5. Conclusions

Through the inversion study on the dynamic elastic modulus and dynamic Poisson's ratio of moderately weathered dolomite using finite element software, the following conclusions are obtained:

(1) When the constitutive relation of moderately weathered dolomite is simplified to an elastic constitutive relation, the average relative error of the maximum principal stress is 2.9%, and the average relative error of the minimum principal stress is 3.0%, which is reasonable.

(2) When the dynamic elastic modulus of moderately weathered dolomite is 1-1.15 times the static elastic modulus and the dynamic Poisson's ratio is 1-1.24 times the static Poisson's ratio, the results obtained from dynamic calculations using MIDAS/GTS-NX are relatively reasonable.

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