Influence of Ground Water on Blasting Construction of Adjacent Tunnel

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Abstract. During the construction of a mountain tunnel, water-rich strata are often encountered. Current research on the influence of groundwater on the blasting construction of the adjacent tunnel is not in-depth enough. Based on the Yingpanshan tunnel project of Huali Expressway in Yunnan Province, China, this paper analyzes multi-factor couplings such as blasting dynamic load, large-section excavation, groundwater and adjacent construction. An adjacent construction model with a size of 80×80×50m is established by COMSOL Multiphysics software. Considering the change of permeability and elastic modulus of the model, the influence of blasting construction on the adjacent construction is reflected by the vibration velocity of the existing tunnel lining. The results show that the impact of groundwater on the safety of the adjacent structure is mainly related to the permeability, and its influence degree increases with the water pressure. In the water-rich stratum with high permeability of rock mass, it is necessary to pay attention to the influence of groundwater on the safety of adjacent blasting construction.

Keywords: Tunnel construction, Fluid-Structure interaction, Ground water, Adjacent construction

1. Introduction

With the continuous progress of engineering construction in central and western China, there are quantities of long-distance large section tunnels. And the proportion of tunnels constructed by drilling and blasting method is still the largest. In the process of drilling and blasting tunnel construction, there are more and more adjacent constructions with small spacing, such as the new tunnel passing through the existing tunnel from the top or the bottom, the interaction between the two main tunnels of the separated tunnel, and the intersection between the main tunnel and the inclined shaft. In terms of the impact of blasting construction on the adjacent construction, relevant scholars have done plenty of research work. In situ monitoring method is often used to monitor the vibration effect of blasting construction on the adjacent tunnel (Ye et al., 2011; Yang et al., 1994; Shin et al., 2011). The dynamic response of rock under blasting load has been studied in laboratory (He et al., 2019; Huang et al., 2020), and the vibration response of the existing tunnel during blasting has been analyzed in detail by numerical
simulation method (Qiao et al., 2007; Ma et al., 2008; Yu et al., 2019; He et al., 2019). It can be seen from the research and analysis that blasting will have a significant impact on the existing buildings under adjacent construction, so it is necessary to optimize the safety distance and construction parameters. Due to the complexity of underground engineering, the influence of groundwater has not been taken into account in the existing research of adjacent construction. A large number of rock engineering accidents are related to the action of groundwater seepage. The high groundwater pressure, in-situ stress, and excavation disturbance are the main factors affecting the stress and deformation of surrounding rock, forming the fluid-solid coupling effect of groundwater seepage field and rock mass in-situ stress field (Li et al., 2008; Chen et al., 2013; Liu et al., 2015; Yan et al., 2016; Liu et al., 2018). Therefore, the fluid-structure coupling analysis of rock mass safety is closer to the actual situation and more effective analysis method.

To study the influence of groundwater on the adjacent construction. Based on the Yingranshan tunnel in Yunnan Province, this paper establishes a fluid-structure coupling numerical model considering the interaction between groundwater and rock mass, analyzes the influence of different pore water pressure and different lithology on the adjacent construction. The results of the study are of guiding significance for the design of adjoining construction under the condition of abundant water.

2. Fluid-Structure interaction method
Rock is a kind of porous medium with low permeability. The interaction between rock and groundwater needs to be analyzed by the Fluid-Structure interaction method. Fluid-Structure Interaction (FSI) is a multi-physical field coupling between the laws of fluid mechanics and structural mechanics. This phenomenon is characterized by the interaction between the deformed structure and the surrounding or internal fluid. The coupling method of Darcy's law and solid mechanics are generally used in Fluid-Structure interaction in saturated porous media.

2.1. Fluid Flow — Darcy's Law
Darcy's law describes the flow field in the poroelastic model. The fluid equation comes from mass conservation.

$$\rho_f \frac{\partial p_f}{\partial t} + \nabla \cdot (\rho_f \mathbf{v}) = -\rho_f \alpha_b \frac{\partial}{\partial t} \varepsilon_{vol}$$  \hspace{1cm} (1)

Where, $\rho_f$ is the fluid density, $S$ is the poroelastic storage coefficient related to the compressibility of fluid and solid, $p_f$ is the fluid pore pressure, $\mathbf{v}$ is the seepage velocity tensor, $\frac{\partial \varepsilon_{vol}}{\partial t}$ is the rate of change in volumetric strain of the porous matrix, and $\alpha_b$ is the Biot-Willis coefficient which depends on the elastic properties of the porous matrix.

2.2. Solids Deformation — Solids mechanics
The constitutive relation controlling the elastic behaviour of porous materials is related to stress, strain, and pore pressure:

$$\sigma = D \varepsilon - \alpha_b p_f I$$  \hspace{1cm} (2)

Where, $\sigma$ is the stress tensor, $\varepsilon$ is the strain tensor, $\alpha_b$ is the Biot-Willis coefficient, and $p_f$ is the fluid pore pressure. $D$ is the elasticity matrix.

The Navier's equation of solid equilibrium considering the inertia term is

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} - \nabla \cdot (D \varepsilon - \alpha_b p_f I) = \mathbf{f}$$  \hspace{1cm} (3)

Where, $\rho$ is the porous medium density, $\mathbf{u}$ is the displacement tensor, $\mathbf{f}$ is the volumetric force, which is gravity in this paper.

It is evident that in fluid-solid coupling, the pore pressure of the fluid is added to the stress tensor of solid mechanics as an additional isotropic term. At the same time, when the displacement and
deformation of the structure occur, the change of volume strain and the compression or expansion of porous media and fluid will affect the evolution of fluid characteristics and pore pressure field distribution.

3. Fluid-Structure coupling numerical simulation

3.1. Simulation Project
This study utilizes COMSOL Multiphysics field coupling software to study the effect of underground water in the blasting construction of an adjacent tunnel. Based on the Yingpanshan tunnel project in Yunnan Province of China, the adjacent construction section of the right line of No. 1 inclined shaft and the left line of the tunnel is selected for the present numerical study. The height of the right line of the No.1 inclined shaft is 5.83 m, and its cross-sectional area is 29.35 m², the height of the left mainline tunnel is 7.10 m, and its cross-sectional area is 65.13 m², its buried depth is 535m. The minimum clear distance between them is 4.5m. According to relevant data and blasting control theory, the controlled excavation length of this section is taken as 0.7m. The schematic diagram of the simulation calculation scheme is shown in Figure 1. The red dots are the location of the monitoring points of blasting vibration velocity, which is explained in detail in section 4.1 of the present paper.

![Figure 1. Simulation calculation program diagram.](image1)

3.2. Finite element model
According to the design size, spacing, and impact range of blasting vibration of the tunnel in the project, the length, width, and height of the model are determined as 80m×50m×80m. The calculation model grid is shown in Figure 2. The soil around the model is divided into mapping grids, and the domain near the tunnel is refined. The whole model is divided into 48824 grid units.

![Figure 2. Calculation model grid.](image2)
3.3. The parameters of the model

The representative rock masses are selected from the geological exploration report, and their physical and mechanical parameters are shown in Table 1. E is the elastic modulus, \( \nu \) is the poisson ratio, \( \gamma \) is the gravity density, \( \kappa \) is the permeability, \( \varepsilon_p \) is the effective porosity, \( c \) is the cohesion, and \( \varphi \) is the internal friction angle.

| No. | Lithology                    | E (GPa) | \( \nu \) | \( \gamma \) (kNm\(^3\)) | \( \kappa \) (m\(^2\)) | \( \varepsilon_p \) | \( c \) (MPa) | \( \varphi \) (°) |
|-----|------------------------------|---------|----------|-----------------------------|-------------------------|----------------|-------------|-------------|
| 1   | Dolomite/                      | 2.0     | 0.35     | 26.5                        | 8.044 \times 10^{15}    | 0.023          | 0.25        | 30          |
|     | Moderately weathered          |         |          |                             |                         |                |             |             |
| 2   | Gneiss/                        | 8.0     | 0.28     | 27.0                        | 2.019 \times 10^{14}    | 0.078          | 0.70        | 42          |
|     | Slightly weathered            |         |          |                             |                         |                |             |             |
| 3   | Sandstone/                     | 1.3     | 0.39     | 25.8                        | 4.460 \times 10^{13}    | 0.140          | 0.10        | 33          |
|     | Moderately weathered          |         |          |                             |                         |                |             |             |
| 4   | Quartz diorite/                | 2.0     | 0.35     | 26.5                        | 3.039 \times 10^{12}    | 0.200          | 0.25        | 30          |
|     | Strongly weathered             |         |          |                             |                         |                |             |             |

3.4. Initial settings and boundary conditions

The buried depth of the numerical simulation area is more than 500m, with relatively high in-situ stress. According to the geological exploration data, the in-situ stress is applied to the model domain in the form of prestress.

There are several kinds of boundary conditions in numerical simulation, such as fixed boundary, viscous boundary, and elastic boundary. The blasting vibration wave will cause the oscillation reflection wave at the fixed boundary, resulting in the distortion of the calculation result. Previous studies show that the viscoelastic boundary is suitable for explosion vibration analysis (Qiao et al., 2007). In COMSOL Multiphysics software, the low-reflecting boundary condition takes the material data from the adjacent domain in an attempt to create a perfect impedance match for both pressure waves and shear waves. Therefore, the low-reflecting boundary is selected as the boundary condition of solid mechanics in this paper.

As shown in Table 2, several hydraulic head heights are set in the vertical direction of the model to explore the effect of water pressure conditions on blasting adjacent construction.

| Hydraulic head | 0m  | 100m | 200m | 300m |
|----------------|-----|------|------|------|
| Hydraulic pressure | \( \backslash \) | low  | medium | high |

3.5. Blasting load

For the simulation of blasting dynamic load, the same equivalent blasting dynamic pressure load is usually applied on the boundary of the blasting area. The National Highway Institute (US) suggests that the dynamic pressure formula of blasting vibration attenuation with time should be considered:

\[
P_{det} = \frac{4.18 \times 10^{-3} \times Sge \times V_c^2}{1 + 0.8Sge} \tag{4}
\]

\[
P_h = P_{det} \times \left( \frac{d}{d_h} \right)^3 \tag{5}
\]
$P_{\text{det}}$ is the detonation pressure, kN/m$^2$; $P_B$ is the decoupled detonation pressure, kN/m$^2$; $V_e$ is the detonation velocity, m/s; $d_c$ is the charge diameter, mm; $d_h$ is the borehole diameter, mm; $s_{ge}$ is the specific gravity of explosives.

Based on the above formula, the time function relationship is considered, Statfield proposed the advanced calculation formula of blasting load:

$$P_B(t) = 4P_B\left(\exp\left(-\frac{Bt}{\sqrt{2}}\right) - \exp\left(-\sqrt{2}Bt\right)\right)$$

(6)

$B$ is the load factor and set as 16338, which is the dynamic pressure generated by every 1 kg of explosive. A time-history of blasting under a single charge in this paper is shown in Figure 3.

![Figure 3. Time-history of blasting load.](image)

4. Results and analysis

4.1. Negative position of adjacent blasting construction

The cloud chart of existing adjacent tunnel vibration velocity at different times under typical calculation conditions is shown in figure 4. It is clear that the position where the adjacent blasting construction has the most significant impact on the existing tunnel is near the blast-front side, and more precisely, the locations with the highest vibration velocity occur at the crown or hance of the tunnel.

![Figure 4. Cloud chart of existing adjacent tunnel vibration velocity.](image)

For exploring the most adverse impact position of adjacent blasting construction, monitoring points are set at the crown and the hance on both sides of the existing tunnel to monitor the change of vibration velocity. The location of the monitoring points is shown in the red dots in Figure 1. The transient analysis is used to monitor each position under different conditions continuously, and it can derive the vibration
velocity time history. Figure 5 gives the maximum vibration velocity of each monitoring point under each condition.

**Figure 5.** Maximum vibration velocity at different positions.

For different lithology and hydraulic head, the maximum vibration velocity of the existing tunnel in the adjacent construction appears at the crown. That is, the most disadvantageous position for blasting adjacent construction is the existing tunnel vault. Therefore, the analysis follows will be based on the vibration velocity of the crown lining.

4.2. **Effect of different lithologies on blasting vibration**

The vibration velocity time histories of four kinds of rock masses under different hydraulic pressure are shown in Figure 6.
Figure 6. Time-history of vibration velocity.

The vibration velocity curves of No. 1 and No. 2 lithology show no apparent change under different hydraulic pressure. However, the vibration velocity curve of No. 3 and No. 4 lithology is different under several hydraulic pressure. As shown in Table 1, the permeability coefficient of No. 3 and No. 4 rock mass is relatively large compared with that of No. 1 and No. 2 rock mass.

By comparing and analyzing the lithological parameters, it can be found that the permeability at the four lithologies differs significantly, and the elastic modulus variability is also significant. To eliminate the interference of elastic modulus and to further explore the law, more specific conditions are supplemented for calculation. Additional calculation conditions are shown in Table 3. The values of each parameter are taken from the representative rock masses in the engineering geological exploration report, i.e. the four rock masses in Table 1.

Table 3. Calculation conditions.

| No. | E(GPa) | $\kappa$ ($m^2$) | No. | E(GPa) | $\kappa$ ($m^2$) | No. | E(GPa) | $\kappa$ ($m^2$) |
|-----|--------|-----------------|-----|--------|-----------------|-----|--------|-----------------|
| 1-1 | 1.3    | $8.044 \times 10^{-15}$ | 2-1 | 2.0    | $8.044 \times 10^{-15}$ | 3-1 | 8.0    | $8.044 \times 10^{-15}$ |
| 1-2 | 1.3    | $2.019 \times 10^{-14}$ | 2-2 | 2.0    | $2.019 \times 10^{-14}$ | 3-2 | 8.0    | $2.019 \times 10^{-14}$ |
| 1-3 | 1.3    | $4.460 \times 10^{-13}$ | 2-3 | 2.0    | $4.460 \times 10^{-13}$ | 3-3 | 8.0    | $4.460 \times 10^{-13}$ |
| 1-4 | 1.3    | $3.039 \times 10^{-12}$ | 2-4 | 2.0    | $3.039 \times 10^{-12}$ | 3-4 | 8.0    | $3.039 \times 10^{-12}$ |

4.3. Effect of permeability

Figure 7 shows the maximum vibration velocity curve of the crown lining of the existing tunnel under different calculation conditions. It can be seen that the vibration velocity generally indicates an upward trend with the increase of hydraulic head. At the same elasticity modulus, the vibration velocity with low permeability (e.g. 1-1, 2-1, 3-1) changes little with increasing hydraulic pressure. With the increase of permeability, the changing trend of vibration velocity with hydraulic pressure becomes more and more significant.
4.4. Effect of elastic modulus
Figure 8 shows the maximum, minimum, and average values of the peak vibration velocity of all calculation conditions under three different elastic modulus. For each elastic modulus, the difference of vibration velocity at the crown lining is caused by the change of permeability and hydraulic pressure. The minimum value comes from the calculation conditions without considering groundwater. The maximum amount is the vibration velocity at which the rock mass takes the maximum permeability and the water level is the highest (300m). By calculation, the deviation of extreme value from the average value is about 15%. This part of the change in vibration velocity can be considered as the effect of groundwater.

5. Conclusion
Under the most unfavorable condition when the new tunnel is excavated to the axis of the existing tunnel, the maximum vibration velocity of the existing tunnel lining occurs at the tunnel vault.

The degree of effect of groundwater on blasting vibration is related to permeability. For rock mass with low permeability (when the magnitude of permeability is at $10^{-15} \text{m}^2$ level), groundwater has little influence on adjacent construction. With the increase of permeability, the water-rock coupling becomes more apparent. With the rise of groundwater pressure, the peak vibration velocity of existing tunnel vault lining increases, which is related to permeability.
The vibration speed of the existing tunnel lining in adjacent construction is affected by both permeability and elastic modulus of surrounding rock. The elastic modulus determines the foundation size of vibration speed. On this basis, it varies within a specific range with groundwater level, especially for rock mass with high permeability. In this study, the maximum vibration velocity of the surrounding rock with the highest permeability changes by 15% relative to the average value under the highest water pressure. It can be seen that the existence of groundwater has a significant impact on adjacent construction, which should be paid attention to in the subsequent construction design.

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