Dynamic failure evolution of surrounding rock in a long tunnel with different unfavorable geological structure zones under non-uniform seismic input

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Abstract: Earthquake damage investigations show that damage often occurs in complex geological sections with unfavorable geological structures along a long tunnel. And the unique earthquake damage phenomena are the result of non-uniform ground motion generally. In order to study dynamic failure evolution of surrounding rock in a long tunnel with different unfavorable geological structure zones under earthquake. Therefore, a variety of schemes for dynamic analysis of a long tunnel with different lithology and thickness unfavorable geological structure zones is carried out through non-uniform ground motion input. Firstly, based on stochastic process theory, multiple time history curves of different ground motions that can reflect the traveling wave effect and attenuation effect for long tunnels are generated. Then, the dynamic response of the surrounding rock in the tunnel is analyzed through inputting these non-uniform ground motions. By analyzing the variation of shear plastic strain increment and plastic volume in surrounding rock, the characteristics of the potential failure surface with the earthquake time history in the surrounding rock of the tunnel with different unfavorable geological structure zones are studied. On this basis, the main influencing factors and the degree of influence on the dynamic damage of the surrounding rock of the long tunnel with unfavorable geological structure zone under non-uniform ground motions are evaluated. The results show that the unfavorable geological structure zone has a controlling effect on the seismic dynamic response and
destruction of the surrounding rock of the tunnel. Further, the lithology of unfavorable geological structures and the time history of ground motions have a significant impact on the response and damage of surrounding rock.

1. Introduction

For western development strategy, long tunnels, such as highways and railways tunnels, will be built in western China, and they are approaching or crossing the seismically active fault zone. Over several decades, a series of large earthquakes worldwide have led to cracking, collapse, and destruction of underground engineering structures [1-2]. Due to the geological environments that these long tunnels pass through being different, the ground motion effects present strong spatial inconsistencies [3].

Earthquake damage investigations showed that tunnel damage often occurs in complex geological sections along the line, such as fault fracture zones, soft and hard rock interfaces and other unfavorable geological structures. He et al. [4] combined shaking table model tests and numerical calculations to study the acceleration response characteristics, stratum deformation of the surrounding rock and structure, and internal force distribution of the lining structure of tunnel crossing the fault fracture zone. Li [5] pointed out that the dynamic response of tunnel with soft rock is stronger than that of hard rock when the tunnel entrance crosses the soft and hard interface. Zhu et al. [6] analyzed the general law of the displacement, acceleration and stress response of the control points of the tunnel with different fault inclination angles under earthquake.

It can be seen that the researches mainly focused on the dynamic response of the tunnel under uniform ground motion. There is little analysis of the failure evolution of the surrounding rock of the long tunnel with different unfavorable geological structure zones under non-uniform ground motion. Therefore, in this paper, a long tunnel is taken as the research object, and the acceleration time-history curves of non-uniform ground motion are generated based on the stochastic engineering theory. Through the vertical input method, the dynamic failure evolution of the surrounding rock of the long tunnel with different unfavorable geological structure zones under non-uniform ground motions is analyzed.

2. Acceleration time-history curves of non-uniform ground motion and Analysis plan

2.1 Acceleration time-history curves of non-uniform ground motion

Based on the stochastic process theory, the acceleration time-history curves of non-uniform ground motion can be generate, and the formula of acceleration time history at excitation point i-th can be written as

\[ a_i(t) = \sum_{m=1}^{n} \sum_{k=0}^{N-1} A_{im}(\omega_k) \cos[\omega_k t + \theta_{im}(\omega_k) + \varphi_{mk}] \]  

\[ \omega_k = \frac{k}{T_d} \frac{2\pi}{T_d} \]

(1)

(2)
where $A_{im}(\omega_k)$ and $\theta_{im}(\omega_k)$ are the amplitude and phase angle which are related to the $i$-th and $m$-th excitation points, respectively, and they are the function of the $k$-th circular frequency $\omega_k$. $\varphi_{mk}$ is random phase angle. $T_d$ is the duration of acceleration time-history. The improved Kanai Tajimi spectrum is used as the self-spectral density of the every excitation point, and the corresponding parameters can refer to the literature [7]. It is assumed that the length of the tunnel is 1000m, and an acceleration time-history curve is generated every 50m. Thus, a total of 21 acceleration time-history curves are generated, as shown in Figure 1.

![Acceleration time-history curves](image1)

![Maximum acceleration](image2)

**Figure 1.** Acceleration time-history curves of non-uniform ground motion

### 2.2 Analysis plan

It is assumed that there exists a unfavorable geological structure zone crossing the tunnel, as shown in Figure 2. The position where they intersect is the midpoint of the tunnel. Based on different types of unfavorable geological structure zone (such as lithology and thickness), a multi-scheme for dynamic response of the tunnel with different forms of unfavorable geological structure zone has been developed, as shown in Table 1. And assuming the tunnel length of 1000m and burial depth of more than 100m, a three-dimensional numerical model as shown in Figure 2(a) is constructed. The input ground motion is horizontal vibration in the y-direction, and the mode is vertical input.

![Diagram of the unfavorable geological structure zone and numerical model](image3)

**Figure 2.** Diagram of the unfavorable geological structure zone and numerical model

| Table 1. Analysis plan |
|------------------------|
| Number | Thickness (m) | Inclination(°) | Lithology |
|---------|---------------|----------------|-----------|
3. Dynamic failure evolution of surrounding rock

By analyzing the variation of shear plastic strain increment and plastic volume in surrounding rock, the characteristics of the potential failure surface with the earthquake time history in the surrounding rock of the tunnel with different unfavorable geological structure zones are studied as follow.

3.1 Different thicknesses

Table 2 displays the cloud diagram of the shear strain increment of the surrounding rock of the tunnel at different times when the thickness of the unfavorable geological structure zone is 0.5m. It can be seen that the distribution of the shear strain increment of the surrounding rock along the axial direction of the tunnel is different at each moment. When the time of earthquake action is 10s, the shear strain increment of the surrounding rock behind the unfavorable geological structure zone is significantly larger than that in front of the unfavorable geological structure zone. Further, the largest shear strain increment of the surrounding rock occurs in the vicinity of the unfavorable geological structure zone, and the shear strain increment of the surrounding rock on the left and right sides of the tunnel is significantly higher than that of other parts. At 15s, although the shear strain increment of the surrounding rock near the unfavorable geological structure zone is still the largest, the shear strain increment distribution of the surrounding rock along the axial direction of the tunnel has changed. After 20s, the more severely deformed surrounding rocks are concentrated near the unfavorable geological structure zone and a certain distance in front of the unfavorable geological structure zone, and mainly concentrated at the bottom of the tunnel. When the thickness of the unfavorable geological structure zone is 5m, the shear strain increment distribution of surrounding rock along the axial direction of the tunnel is also different at each time, and the shear strain increment of the surrounding rock near the unfavorable geological structure zone is still the largest. Compared with the situation when the thickness of the unfavorable geological structure zone is 0.5m, the shear strain increment distribution of the surrounding rock in the unfavorable geological structure zone location is different at different times. The severely deformed surrounding rock is mainly concentrated at the bottom of the tunnel at 15s. After 20s, the dangerous surrounding rock is mainly concentrated on the top of the tunnel. When the thickness of the unfavorable geological structure zone is 20m, the cloud diagram of the shear strain increment of the surrounding rock of the tunnel at different times is similar to that when the thickness of the unfavorable geological structure zone is 5m.
Table 2. The cloud diagram of the shear strain increment of the surrounding rock of the tunnel at different times when the thickness of the unfavorable geological structure zone is 0.5m

| Time(s) | Along the axial direction of the tunnel | Section at the location of the unfavorable geological structure zone |
|---------|----------------------------------------|---------------------------------------------------------------------|
| 10      | ![Image](example1.png)                  | ![Image](example2.png)                                               |
| 15      | ![Image](example3.png)                  | ![Image](example4.png)                                               |
| 20      | ![Image](example5.png)                  | ![Image](example6.png)                                               |
| 25      | ![Image](example7.png)                  | ![Image](example8.png)                                               |

Figure 3(a) shows the change of the maximum shear strain increment of the surrounding rock of the tunnel with different thicknesses of the unfavorable geological structure zone with time. It can be seen that process of the maximum shear strain increment of the surrounding rock of the tunnel with different thicknesses of the unfavorable geological structure zone with time is similar. The order of the maximum shear strain increment of the surrounding rock of the tunnel with different thicknesses of the unfavorable geological structure zone is 20m>5m=0.5m>0m. When the thickness of the unfavorable geological structure zone is 20m, the maximum shear strain increment is about 0.00015, which is not much different from the maximum shear strain increment of 0.00013 when the thickness of the unfavorable geological structure zone is 0.5m. It shows that the thickness of the unfavorable geological structure zone has no much effect on the maximum shear strain increment of the surrounding rock of the tunnel.

![Image](example9.png)

(a) Different thicknesses

![Image](example10.png)

(b) Different lithologies

Figure 3. The change of the maximum shear strain increment of the surrounding rock of the tunnel
with unfavorable geological structure zone with time

Figure 4(a) is a graph showing the change of the volume of the plastic zone of the surrounding rock of the tunnel with different thicknesses of the unfavorable geological structure zone with time. In general, the change trend of the plastic zone volume of the tunnel surrounding rock with different thicknesses of the unfavorable geological structure zone over time is the same, and the order of its value is 0m=20m>0.5m>5m. Figure 4(b) shows the volume of plastic zone at different axial distances at 25s. Figure 4(b) shows the plastic zone volume in different axial intervals at 25s. It can be seen that the plastic zone volume of the surrounding rock of the tunnel with different thicknesses of the unfavorable geological structure zone also shows a trend of first increasing, then decreasing along the tunnel axis and reaching the maximum near the unfavorable geological structure zone. Although the volume of the plastic zone of the surrounding rock of the tunnel with unfavorable geological structure zone is generally smaller than that when there is no unfavorable geological structure zone, the volume of the plastic zone of the tunnel with unfavorable geological structure zone is larger than that without an unfavorable geological structure zone near the unfavorable geological structure zone, especially the thickness of the unfavorable geological structure zone is 20m. It also shows that the vicinity of the unfavorable geological structure zone is the most dangerous location for the surrounding rock of the tunnel under earthquake.

![Figure 4](image1.png)

(a) Total volume of the plastic zone (b) Volume of the plastic zone in different axial intervals at 25s

**Figure 4.** The volume of the plastic zone of the surrounding rock of the tunnel with different thicknesses of the unfavorable geological structure zone

3.2 Different lithology

Similar to the results with different thicknesses of unfavorable geological structure zones, the shear strain increment distribution of surrounding rocks along the axial direction of the tunnel with different lithology unfavorable geological structure zones is also different at each time. However, the distribution of shear strain increment under different conditions is similar at the same time, and the shear strain increment of surrounding rock near the unfavorable geological structure zone is still the largest. The order of the maximum shear strain increment of the surrounding rock of the tunnel with different lithology unfavorable geological structures is V> worse IV> IV> III. It shows that the better the lithology of the unfavorable geological structure zone, the smaller the deformation of the surrounding rock of the tunnel is, and the smaller the range of deformation and the safer the
surrounding rock is. Moreover, when the lithology of the unfavorable geological structure zone is level V, the maximum shear strain increment of the surrounding rock is significantly larger than other conditions. It shows that the lithology of the unfavorable geological structure zone has a great influence on the maximum shear strain increment of the surrounding rock of the tunnel, especially the level V unfavorable geological structure zone.

In general, the plastic zone volume of tunnel surrounding rock under different lithology unfavorable geological structure zones has a similar trend with time. That is, it increases firstly, and then reaches the maximum at between 10s and 15s, and finally remains unchanged. The order of the maximum shear strain increment of surrounding rock under different lithology unfavorable geological structure zones is $V > \text{worse IV} > \text{category IV} > \text{III}$. Meanwhile, the plastic zone volume of the surrounding rock of the tunnel with different lithology unfavorable geological structure zones also shows a similar trend with the results with different thicknesses of the unfavorable geological structure zone. Near the unfavorable geological structure zone, the volume of the plastic zone of the tunnel with unfavorable geological structure zone is obviously larger than that without the unfavorable geological structure zone.

![Figure 5](image_url)

(a) Total volume of the plastic zone  (b) Volume of the plastic zone in different axial intervals at 25s

**Figure 5.** The the volume of the plastic zone of the surrounding rock of the tunnel with different lithology unfavorable geological structure zone

4. Conclusion

This paper mainly analyzes the dynamic failure evolution of the surrounding rock of a long tunnel with different unfavorable geological structure zones under non-uniform ground motions. The conclusion is obtained as follows.

1. The largest shear strain increment of the surrounding rock occurs in the vicinity of the unfavorable geological structure zone, and the shear strain increment of the surrounding rock on the left and right sides and at the bottom of the tunnel is significantly higher than that of other parts.

2. The thickness of the unfavorable geological structure zone has no much effect on the maximum shear strain increment of the surrounding rock of the tunnel.

3. The lithology of the unfavorable geological structure zone has a great influence on the maximum shear strain increment of the surrounding rock of the tunnel, especially the level V unfavorable geological structure zone.

4. The volume of the plastic zone of the tunnel with unfavorable geological structure zone is
obviously larger than that without the unfavorable geological structure zone near the unfavorable geological structure zone.

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