Stability analysis of an underground excavation with reference to dynamic loading and groundwater

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Abstract: Research shows that dynamic loadings, such as seismic events and explosive loadings, and groundwater are of great significance to the stability of an underground excavation in a jointed rock mass. To date, some achievements have been made in these two aspects. However, the stability analysis of an underground excavation in a jointed rock mass seldom takes account of and reports the effects of dynamic loading and groundwater.

The Distinct Element Method (DEM) is used to analyze the influence of the peak velocity and frequency spectrum which are the primary factors in the analysis of the seismic wave commonly induced by an earthquake. The influence of the groundwater on the stability of the underground excavation in a jointed rock mass is also investigated. This research shows that groundwater level plays an important role, whereas the other two hydraulic parameters (joint permeability and hydraulic aperture at zero normal stress) are much less significant in the stability analysis. Preliminary discussions on how the dynamic loadings and groundwater influence the stability of the surrounding rock mass are included. The prediction of the stress field and the displacement field in these coupled conditions are also made.

Résumé: Recherche l'exposition qui les chargements dynamiques, tels que des événements séismiques et des chargements explosifs, et des eaux souterraines sont de grande importance à la stabilité d'une excavation souterraine dans une masse jointe de roche. Actuellement, quelques accomplissements ont été faits dans ces deux aspects. Cependant, l'analyse de stabilité d'une excavation souterraine dans une masse jointe de roche rarement considère et rapporte aux effets le chargement dynamique et les eaux souterraines. La méthode distincte d'élément (DEM) est employée pour analyser l'influence de la vitesse et du spectre maximaux de fréquence qui sont les facteurs primaires dans l'analyse de la vague séismique généralement induite par le tremblement de terre. L'influence des eaux souterraines sur la stabilité de l'excavation souterraine dans une masse jointe de roche est également étudiée. Cette recherche prouve que le niveau d'eaux souterraines joue un rôle important, tandis que les deux autres paramètres hydrauliques (perméabilité commune et ouverture hydraulique à l'effort normal zéro) sont beaucoup moins significatifs dans l'analyse de stabilité. Des discussions préliminaires sur la façon dont les chargements et les eaux souterraines dynamiques ont influencé la stabilité de la masse environnante de roche sont engagées. Les prévisions du champ de contrainte et du champ de déplacement en cela des conditions couplées est également faites.

Keywords: dynamic loading, earthquake, water table

INTRODUCTION

The stability of jointed rock is of great concern in the design of the underground opening. Generally, the factors influencing the stability of the jointed rock are its structure and environmental factors including groundwater and seismic activity. Many underground structures in the jointed rock are stable in usual conditions, but become unstable, or even fail under seismic loading or when significant groundwater is present (Tao and Chang 2000).

Groundwater flows in the discontinuities in the rock. Joint deformation will change the hydraulic aperture of the joint and influence the joint permeability. Groundwater flow will influence the pore pressure and the mechanical properties of the joint. Therefore, the stress field and the flow field interact with each other suggesting that the deformation of the whole rock mass results from both. Hence, the coupled analysis of the stress/flow field is of great significance.

Besides groundwater, seismic activity is also an important factor which has to be taken into consideration in the analysis of the stability of the jointed rock. Sharma and Judd (1991) established a database containing 192 reports from 85 earthquakes throughout the world which showed that some underground openings showed minor, medium (or even major damage) following earthquakes. Therefore, seismic loading and its effect make be taken into account in the design of such important underground facilities as a power house or repository (Tao and Zhang 1998). Long term prediction of the earthquake is feasible. Short term prediction, however, is not very reliable. Aseismic design is often used rather than making predictions (Zhang et al. 2002). At present, understanding of the dynamic response of the underground structures is not sufficient (Tao et al. 1998). The dynamic reaction and deformation (or failure mechanism) of the underground excavation under seismic loading follows its particular rule and the success of the underground facilities directly depends on the stability of the joint rock. From this the importance of study of the dynamic response of the surrounding rock mass of the underground opening is clear.

Most researchers simply focus on a single factor, either groundwater or seismic loading, when studying the stability of underground openings. In reality, the jointed rock is affected by the groundwater conditions at the time of the seismic loading. The mechanical reaction of the jointed rock with the coupling loadings follows particular rules and studying the stability under the coupled loadings approach appears closer to reality and more meaningful.

THE INFLUENCE OF THE EARTHQUAKE ON THE UNDERGROUND OPENINGS

The failure of an underground opening induced by an earthquake is a common seismic hazard. With the implementation of China's West Development Strategy, a lot of hydro projects are to be constructed in earthquake prone areas. The mechanical response of the underground opening and its safety under seismic loading is difficult to assess for these construction projects.

The description of the model and the parameters

The underground opening used for the model is 12 m square with an overburden depth of 300 m. The length of the artificial boundary is assumed as 7 times that of the underground cavern. Concrete liners are used as the supporting system. The material parameters assumed are shown in Table 1. A compressive stress of 7.5 MPa is applied in both vertical and horizontal directions (increasing linearly with depth) to model the initial stress field. The dynamic loading is applied as a sinusoidal shear wave and introduced at the base of the model with non-reflecting boundaries. Rayleigh damping is used with critical damping ratio ξ_i=0.005. The centre frequency f_{min} is dependant on the input frequency of the seismic wave and is usually made equal to the frequency of the seismic wave.

Table 1. Parameters of the model

Parameters for intact rock		Parameters for joints		Parameters for concrete	
Density(ρ)	2500kg/m^3	Normal stiffness(K_n)	10GPa/m	Density(ρ)	2400kg/m3
Bulk modulus(K)	16.67GPa	Shear stiffness (K_s)	10GPa/m	Elastic modulus(E)	36GPa
Shear modulus(G)	10GPa	Friction angle(φ)	30^0	Poisson's ratio(μ)	0.2
		Cohesion(c)	0MPa	Compressive strength(σ_c)	39.5MPa
		Tensile strength(σ_t)	0MPa	Tensile strength(σ_t)	2.95MPa

Amplitude and frequency are two important factors for the seismic wave. The amplitude and the frequency of the seismic wave have significant influence on the stability and potential failure of the joint rock (Tao et al. 1998). The influence of these two parameters on the stability of the underground opening is investigated in this section.

Generally, seismic waves can be analyzed into several sinusoidal waves with different amplitudes, different frequencies and different phase angles. Studies on the mechanism under the simple wave condition contribute to the understanding of more complex wave form seismic waves. The sinusoidal shear wave varies with the type of velocity history as the dynamic loading is introduced at the base of the model. The parameter peak velocity V_s is investigated to analyze its influence. In the calculation, V_s=0.05 m/s, 0.10 m/s, 0.5 m/s, 1.0 m/s, 1.5 m/s are used respectively.

Both the analytical solution based on the elastic mechanics and the numerical solution shows that the dominant frequency of the model is within the range of 5.0 Hz to 6.0 Hz. Throughout the calculations, the frequencies f=0.05 Hz, 0.1 Hz, 6 Hz, 10 Hz, 20 Hz, 30 Hz, 50 Hz, 70 Hz are used respectively to investigate its influence.

The results and the analysis

The influence of the peak velocity

The axial force histories of the structural elements in the position of interest in the underground opening, (for instance, the centre of the excavation floor and the roof, the centre of the left wall and the right wall, left-top corner, right-top corner, left-bottom corner and the right-bottom corner) are recorded. From the axial force histories the maximum axial force during the seismic loading can be deduced. Thus, the variation of maximum axial force in structural elements with peak velocity V_s can be obtained, see figure 1.

During the dynamic loading, the axial forces of the monitoring structural elements are all negative indicating that they are in compression. In figure 1, the axial forces are displayed in positive sign for convenience. (1roofexca indicates the centre of the roof and 2floorexca the centre of the roof, 3leftwall the centre of the left wall, 4rightwall the centre of the right wall, 5lefttopcorner left-top corner of the excavation, 6righttopcorner right-top corner, 7 leftbottcorner left-bottom corner and 8rightbottcorner indicates the right-bottom corner of the excavation.)

From figure 1 it can be seen that the axial forces of the structural elements around the underground opening increase as the peak velocity V_s rises. The axial force in the four corners are larger that those in the centre of the four sides of the underground opening.

The rate of increase also depends on the frequency of the seismic wave. Figure 1 plots a frequency f=70 Hz, whereas Figure 2 shows f=0.1 Hz. By comparing the figures, it can be seen that for f=0.1 Hz, a piecewise linear function can be used to numerically describe the increasing curve, while for f=70 Hz, a power function $y=x^{\alpha}$ with α<1 or S-shape function may be used to describe the increasing trend. This depends on where the particle is within the surrounding rock of the underground opening stays.

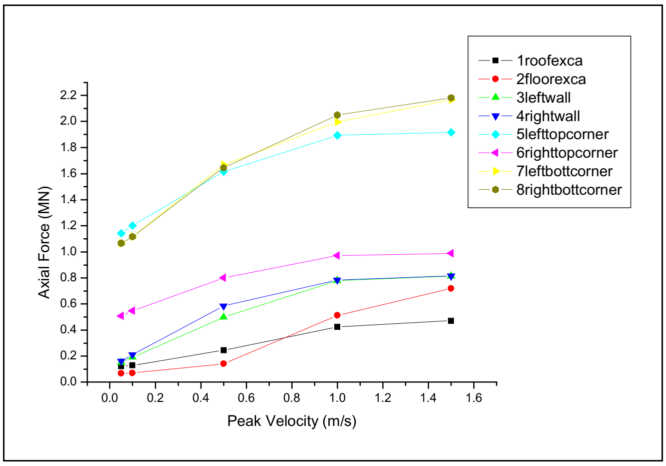

Figure 1. Variation of maximum axial force in structural element with V_s (f=70 Hz)

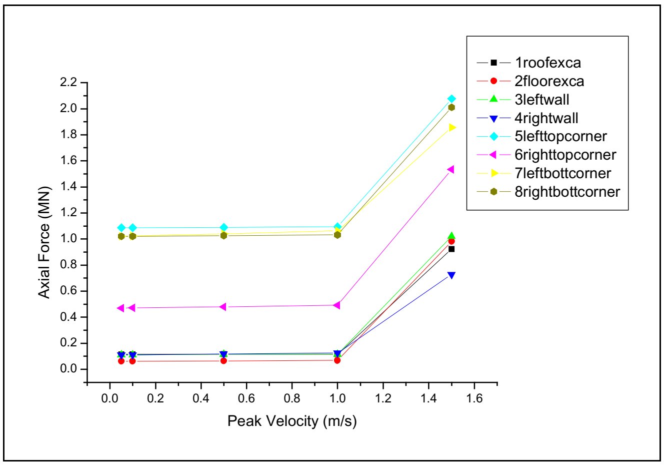

Figure 2. Variation of maximum axial force in structural element with V_s (f=0.1 Hz)

The influence of the frequency

Figure 3 shows the variation of axial force of the structural element at the top-left corner with seismic frequency. From this figure, it can be seen that the axial force of the structural element reaches a maximum when the seismic frequency f equals 6 Hz which is just within the range of the dominant frequencies of the model. With relatively higher frequencys, for instance, f>20 Hz, the axial force exhibits an increasing trend with seismic frequency. Figure 4 shows the variation of axial force of the structural element in the centre of the floor with seismic frequency. The same conclusion can be drawn as for figure 3.

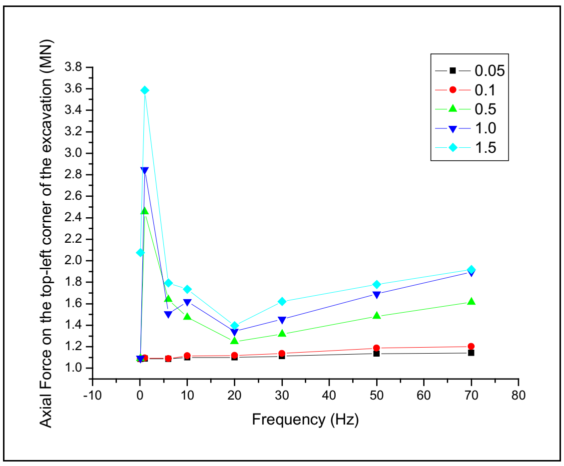

Figure 3. Variation of axial force of the element at top-left corner with the seismic frequency

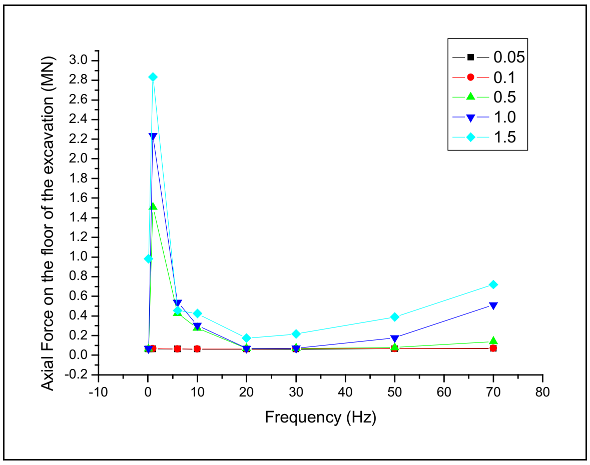

Figure 4. Variation of axial force of the element on floor with the seismic frequency

THE INFLUENCE OF THE GROUNDWATER ON THE UNDERGROUND OPENINGS

The groundwater flows in the discontinuities in the rock mass and the flow rate and pore pressure influence the stress field in the surrounding rock mass and the how the stress will be redistributed. Hence, they contribute (to some degree) to the stability of the underground opening. In this section, a fully coupled mechanical-hydraulic analysis is performed to try to better understand the mechanical response of the underground opening to groundwater.

The description of the model and the parameters

As a starting point *wt* is defined as the distance between the water table and the centre of the underground opening. Since the overburden depth of the underground opening is very large, it can be assumed that the water table is well above the underground opening which means the entire model assumes fully saturated conditions. Based on this assumption, the hydrostatic stress is introduced along the four boundaries of the model. The boundary stress increase linearly in the vertical direction. At the same time, pore pressure is initialized in the model to balance the boundary stress. The joints' hydraulic mechanical properties are summarized in Table 2.

Table 2. Joints' hydraulic mechanical properties

Fluid density	ρ=1000kg/m^3
Joint permeability factor	*jperm*=3×10^{8}MPa^{-1}s^{-1}
Joint hydraulic aperture with zero normal stress	a_{zero}=0.001m
Joint residual aperture	a_{res}=0.0005m

The results and the analysis

A beam element is used to model the concrete liners in the underground opening. Therefore, the internal forces in the concrete liners are presented in terms of an axial force, shear force and a bending moment. Since the calculated shear force and bending moment are two orders of magnitude smaller than the axial force, as an approximation the internal force can be replaced by the axial force. (Positive axial force N indicates tension and negative N indicates compression.)

Figure 5 shows the comparison of axial force before and after ground water is introduced with *wt*=50 m. From this it can be seen that the internal forces of the concrete liners increase to some extent under the influence of the groundwater, however, the distribution of the internal force changes little. In the plot, blue indicates the internal forces before the groundwater is introduced and black indicates those after the groundwater is introduced.

Figure 6 shows the variation of axial force N with *wt* for the left-top concrete liners. N increases approximately in a parabolic curve.

Figure 7 shows the variation of axial force with *wt* on the roof concrete liners. By comparing Figures 6 and 7, it can be seen that the axial force is dependant on *wt* and where the monitoring points are located. N at the corners shows compression and increases with *wt*. N in the centre of the four sides of the underground opening shows compression if *wt*<100m and is relatively small scale, while it indicates tension and increases with *wt*.

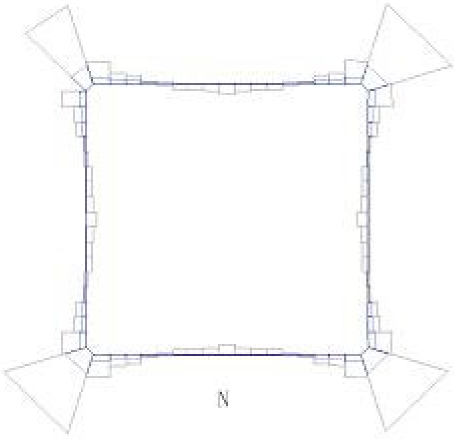

Figure 5. Comparison of axial force before and after ground water is introduced

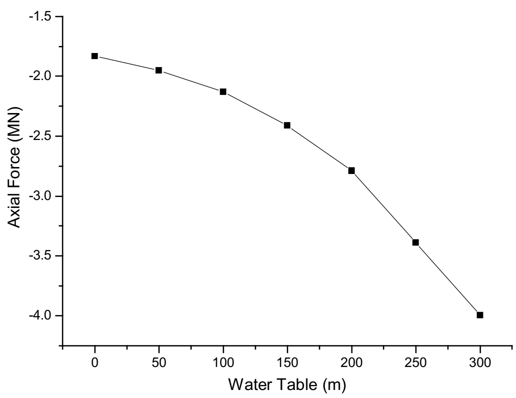

Figure 6. Variation of axial force N with *wt* for the left-top concrete liners

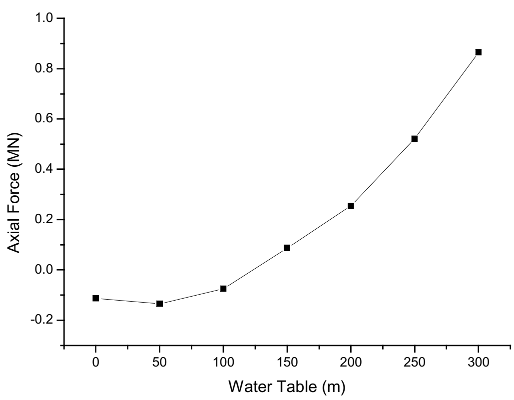

Figure 7. Variation of axial force with *wt* on roof concrete liners

Figure 8 shows that the pore pressures near points A, B and C increase with *wt*. Point A is near the centre of the roof, point B is near the centre of the left wall and point C is near the centre of the floor. From the plot, it can be seen that the pore pressure near the three points increases linearly which indicates that the hydrodynamic pressure is very small compared with the pore pressure and can be ignored. The reason for this is that the flow rate is very low (in the magnitude of $10^{-7}m^3/s$).

In the fluid analysis of groundwater, joint permeability and hydraulic aperture with zero normal stress are two important hydraulic mechanical parameters. However, since the flow rate is very low, in the magnitude of $10^{-7}m^3/s$, the additional stress induced by the groundwater is very small compared with the initial stress. The calculation shows that the influence of these two parameters is much smaller than that of *wt*.

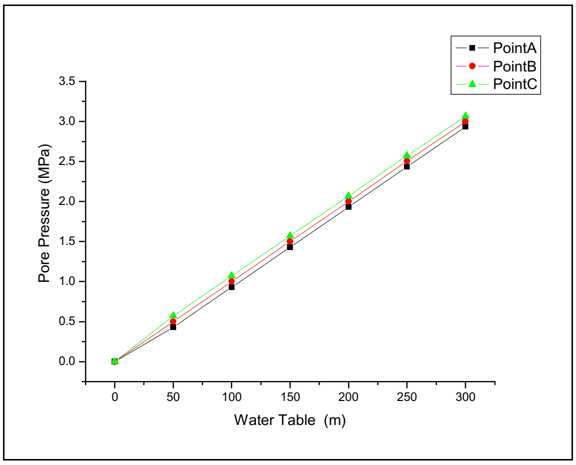

Figure 8. Variation of pore pressure in the monitoring points A, B, C with *wt*

THE INFLUENCE OF GROUNDWATER AND EARTHQUAKES ON UNDERGROUND OPENINGS

Groundwater is a long-term loading, whereas earthquakes occur suddenly and their impact is limited in duration but may cause great damage to the underground opening. Considering both these environmental factors in the study will be more useful. In this section, the distinct element method is used to analyze the mechanical reaction of the underground opening in the jointed rock with reference to these two factors. In the analysis, by recording the internal force histories of the concrete liners it is possible to understand the mechanical response to some degree and hence to provide some guidance for the design and construction of the underground structures.

After excavating the underground opening, groundwater is introduced with *wt*=50 m. A steady-state flow mode for fluid analysis assumed for the calculation. When the flow of the groundwater approaches equilibrium, sinusoidal shear waves with velocity histories are introduced at the base of the model. The peak velocity V_s equals 0.05 m/s and the frequency equals 6 Hz.

Figures 9 and 10 show the variation of axial force of the element near the bottom-left corner and on the left wall with both factors respectively.

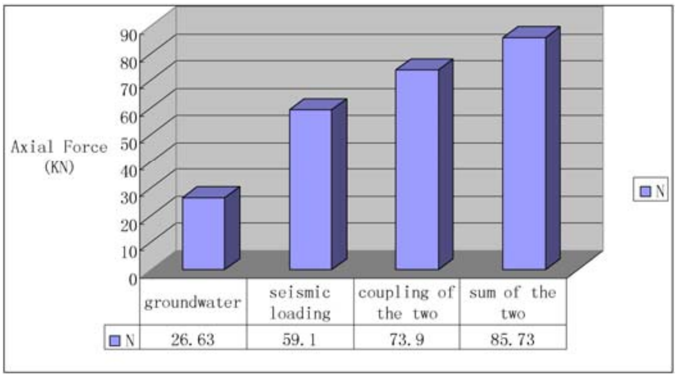

Figure 9. Variation of axial force of element near bottom-left corner with environment factors

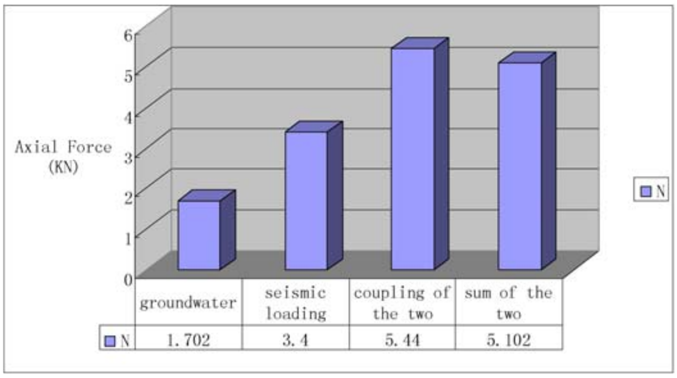

Figure 10. Variation of axial force of element on the left wall with environment factors

In the two plots, the abscissa indicates the environmental factor plotted. *Groundwater* means only the groundwater is plotted, *seismic loading* means only the seismic loading is plotted, *coupling of the two* means the underground opening is assumed to be under the coupled loadings, *sum of the two* means the two values are added numerically. The ordinate indicates the axial forces in the concrete liners.

By comparing the two figures, it is shown that the axial forces under coupling loading are not simply the sum of the two single factors. The *coupling of the two* is larger than *groundwater* or *seismic loading*. This implies that coupled loading will lessen the stability of the underground excavation. The extent of the deterioration, however, depends on the positions of the element being considered. From Figure 9, *coupling of the two* in the corner is smaller than *sum of the two* and the magnitude is of the order of 10 to 100 KN. From Figure 10, *coupling of the two* in the corner is larger than *sum of the two* and the magnitude is of the order of 1 to 10 KN. This indicates that the axial forces at the corner are relatively large and *coupling of the two* is smaller than *sum of the two*, while those in the centre of the sidewall are relatively small and *coupling of the two* is larger than *sum of the two*.

CONCLUSIONS

The Distinct element method is used in this paper to generate a model for the underground opening in jointed rock and to analyze the influence of groundwater and seismic loading together on the mechanical response of the underground excavation.

The main conclusions are:

- The mechanical response of the underground opening increases with the peak velocity of the seismic wave. The nature and the extent of increase depends on the frequency and the particle position.
- Groundwater has influence on the mechanical response. With reference to groundwater, the axial forces on the concrete liners increase. *wt* is a primary factor and the mechanical response increases with *wt*. Joint permeability and hydraulic aperture play much less important roles in the analysis due to the fact that the flow rate is very slow in the model.
- Compared with mechanical reaction of *groundwater* and *seismic loading* considered singly, coupling them gives a larger intensity. However, coupling is not a simple sum of the two. *Coupling of the two* reduces the stability of the underground opening – the extent of the reduction depends on where the structural element stays.

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